PARAMETER OPTIMIZATION FOR CAPP OF TANDEM COLD ROLLING MILL

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CERTIFICATE

It is certified that the work contained in the thesis entitled, "**Parameter Optimization For CAPP of Tandem Cold Rolling Mill**", by "**Ajay Kumar**", has been carried out under our supervision and that this work has not been submitted elsewhere for a degree.

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ABSTRACT

In the present work an effort has been made to analyze, design and implement a parameter optimization module for computer aided process planning system of tandem cold rolling mill.

The objective is to estimate the optimal number of stages through which the desired reduction from a specific blank can be arrived at. The other principal decision variables are reduction per stage, inter-stand tensions between the consecutive stages, and velocity of roll in the first stage. All these decision variables work together to generate the process plan. The list of possible lubricants, roll diameters, roll materials corresponding to the sheet material are collected and stored. To help the user in deciding the roll material, roll diameter, lubricant the lists are provided in the input module of the system. The optimal process parameters are determined by using real coded genetic algorithm technique. The system has been designed on ANSI C compiler compatible with UNIX environment.

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NOMENCLATURE

D_b	:	Back-up roll diameter (m)
D_w	:	Work-roll diameter (m)
D_{e_i}	:	Flattened work-roll diameter at i^{th} stage (m)
e_i	:	Equivalent strain at i^{th} stage
E	:	Young modulus of elasticity of the work-roll material (N/m^2)
f_i	:	Slip in i^{th} stage
f_{R_i}	:	Specific roll separating force at i^{th} stage (N/m)
$f_{R_{max}}$	:	Maximum roll separating force (N/m)
H	:	Heat transfer coefficient of the lubricant (W/m^2 $°C$)
h_{n_i}	:	Thickness of the strip at i^{th} stage (m)
h_0	:	Blank thickness (m)
h_{i-1}	:	Sheet thickness at the entry of i^{th} stage (m)
h_i	:	Sheet thickness at the exit of i^{th} stage (m)
h_n	:	Thickness of the final product (m)
K_1	:	First characteristics of the lubricant
K_2	:	Second characteristics of the lubricant $(m/sec)^{-1}$
L_{R_i}	:	Length of arc of contact at i^{th} stage (m)
r_i	:	Reduction at i^{th} stage
r_t	:	Total reduction
q_r	:	Roughness of the work-roll (μm)
q_s	:	Roughness of the strip (μm)
V_{R_i}	:	Velocity of the work-roll at i^{th} stage (m/sec)
V_{e_i}	:	Velocity of the strip at the exit of i^{th} stage (m/sec)
V_{max_i}	:	Maximum velocity of the work-roll at i^{th} stage (m/sec)
x_{n_i}	:	Non-dimensional neutral angle at i^{th} stage
p_{e_i}	:	Power to apply interstand tension at i^{th} stage (W/m)
p_i	:	Total power consumed at i^{th} stage (W/m)
ϕ_{n_i}	:	Neutral angle at i^{th} stage
ϕ_{b_i}	:	Angle of bite at i^{th} stage
σ_y	:	Annealed yield strength of the blank (N/m^2)
σ_{c_i}	:	Constrained yield strength at i^{th} stage (N/m^2)
σ_{d_i}	:	Dynamic yield strength at i^{th} stage (N/m^2)
σ_{i-1}	:	Back tension at i^{th} stage (N/m^2)
σ_i	:	Front tension at the i^{th} stage (N/m^2)
σ_{av_i}	:	Average tension at i^{th} stage (N/m^2)
T_{R_i}	:	Temperature of the work-roll ($°C$)
T_{c_i}	:	Temperature of oil at inlet ($°C$)
τ_i	:	Specific torque per spindle at i^{th} stage (N)

Chapter 1

Introduction

Rolling is one of the most widely used method of processing metals. It is estimated that 80 percent of the steel stock is processsed at least once in roll mill. Being a continuous process, rolling gives higher output and higher productivity as setups are fewer. It can produce a wide range of products with a higher degree of conformity. Rolled metals, both ferrous and non-ferrous, are in universal use and in no branch of metal fabrication greater progress has been achieved than in the manufacture of sheets and strips. This progress has included studies of rolling both with regard to the plant, the equipment employed and the behavior of the metals when subjected to this type of deformation.

Rolling can be defined as a compressive deformation process in which there is continuous deformation with one or more rotary tools called *rolls*. Basically the operation involves passing the work material between two rolls rotating in opposite directions at the same speed. The roll grips the material and reduces its thickness. The reduction from the initial to final desired thickness may require more than one stage of rolling, called ***tandem*** or ***multi-stage*** rolling.

The important parameter influencing the behavior of metal during rolling is its temperature. If the rolling is performed at a temperature higher than the recrystallization temperature, it is known as ***hot rolling***. In hot rolling

the deformed grains have enough time for relieving the stresses and for recrystallization. When the rolling temperature of the metal is below the recrystallization temperature, it is known as ***cold rolling***. Generally, steel ingots and billets are hot rolled into flat or structural forms and then the hot rolled flat stocks are further cold rolled into plates and often into sheets or foil forms.

Rolling is a very complex metal forming process. The process parameters such as roll separating force, torque etc. show time variability. Even the material properties such as stress-strain characteristics changes with time due to temperature and strain rate effects, and frictional properties also change due to the variation in temperature. The requirements of high degree of shape and size conformity and of imparting the desired mechanical and metallurgical properties to the finished product, puts a severe demand on accurate determination of process parameters for optimal control. The developments in the rolling mill have led to the importance of implementation of process models at the plant level. These models are incorporated into the process control algorithms to obtain defect free flat stock. In these control algorithms product dimensions are monitored in real time. Dimensional error is controlled by continuously adjusting the applied or external process parameters such as ***rolling speed***, ***roll separating force*** and ***roll torque***. In addition, for adequate design of tooling and machines, it is necessary to know the pressures and forces generated at the die-workpiece interface during the deformation process. In the rolling process, these forces are the ***normal pressure*** and the ***frictional stresses*** generated at the roll-sheet interface. These forces are, however, difficult to measure because the interface is not easily accessible and the available transducers cannot measure these parameters without affecting the interface conditions. The need for a priori determination of roll forces and roll torque cannot be over-emphasised. This in turn has led to the importance of off-line process planing.

An elaborate discussion on tandem rolling mills is available in reference [3].

1.1 Process Planning

1.1.1 Definition

Process planning is the function within a manufacturing facility that establishes which manufacturing processes and parameters are to be used (including the machines which are capable of performing these processes) to convert a piece part from its initial form to its final form usually predetermined by a design engineer and indicated on engineering drawing. Process planning links design with manufacturing of a product and the process plan contains factors like functional requirement of the product, volume of the output, the operations, tools and equipment necessary, and the estimated manufacturing cost for producing the product.

Inspite of the importance of process planning in manufacturing cycle it is still predominantly a manual activity, leaning heavily on experience, skill and intuition. Dependence on practical experience often precludes a thorough analysis and optimization of the process plan and nearly always results in higher-than-necessary production costs, delays, errors and non-standardization of processes.

The desire to increase quality and reduce lead time and cost, or to improve productivity has led to Computer-Aided-Process Planning (CAPP).

1.1.2 Process Planning Approaches

Two approaches to CAPP are traditionally recognized : the variant approach, and the generative approach. However, with the rapid development of new techniques, many CAPP systems do not easily fit this classification since they combine both approaches.

1.1.2.1 Variant Approach

The variant approach to process planning compares with the traditional manual approach, where a process plan for a new part is created by recalling, identifying and retrieving an existing plan for a similar part from a computerized database of processes and making the necessary modification for the part. In some variant systems parts are grouped in a number of part families, characterized by similarities in manufacturing methods, thus related to group

technology. For each part family, a standard process plan, which includes all possible operations for the family is stored in the system. The standard plan is retrieved and edited for the new part.

1.1.2.2 Generative Approach

In the generative approach, process plans are generated by means of technology algorithms, decision logics, formulae and geometry based data. In case of changes in the manufacturing facilities, or overloading of machines, the generative process plan will automatically generate alternate process plan. The biggest advantage of this approach is that it is fully automatic and does not rely on the specific expertise of the process planner.

Major consideration and features of the CAPP systems are available in reference [8].

1.2 Cold Rolling and Process Planning

A number of complex mathematical models for calculation of different process parameters of rolling are available in the literature. In mathematical models there is always a desire to produce more and more accurate results by generalization of relationships and removing assumptions included in the previous models. If a model turns out to be a valid simulator of the rolling process, then the frequency of its use increases and this often creates a desire for a faster, even lesser accurate, model. Modern cold rolling mills have sophisticated mechanical and automatic controls where time is a important consideration. Moreover there are several sources of time dependent variability in mill operation that can often outweigh the errors inherent in a mathematical model. Obvious examples include material property, roll roughness, changes in frictional coefficient, temperature due to heat transfer etc. Therefore, if a simpler models has a well thought of structure, and represents the key physical aspects of a process, then it is adequate for off-line investigations for the purpose of process planning. For on-line applications, there may be no other alternative apart from introduction of feedback in the form of model coefficient adaptation.

Moreover process planning needs a lot of experience and creativity as it

may not be possible to develop the process plan solely on the basis of logic. Information stored in the form of thumb rules and empirical relations are often analyzed for decision making. Thus a combination of thumb rules and empirical relations, and mathematical models might give an acceptable procedure for the process planning of rolling process.

For a given type of rolling mill and the blank specifications, the process planning for rolling may involve

1. the determination of optimum number of stages,
2. the determination of optimum interstand distance,
3. the determination of interstand tensions,
4. the determination of optimum reduction schedule,
5. the determination of velocity of rolls at each stage,
6. the determination of roll-separating force at each stage, and
7. the determination of optimum power at each stage.

1.3 Literature Survey

A lot of work has been done in the field of rolling, but most of these relate to evaluation of rolling parameters. Very few attempts have been done to analyze the process as a part of integrated decision making.

Avitzur and Van Tyne [1] proposed criterion curves for central bursting. They have followed an upper bound approach by assuming a rigid body rotational fields.

Avitzur [2] followed an upper bound approach for the analysis of cold strip rolling. The analysis has been done on the basis of several simplifying assumptions such as Columb friction between the strip and rolls, and von Mises material with no strain hardening effects, and elastic deformation. The analysis involves calculation of the minimum possible reduction, maximum possible reduction, rolling efficiency, and roll torque. Results have been shown in the form of mathematical expressions and graphs.

Dixit and Dixit [6] have done FEM analysis for the determination of longitudinal residual stresses in the rolled material. The work deals mainly with the influence of process parameters on the residual stress distribution pattern.

Laporok and Thomson [11] proposed a system for optimal tool design. Which includes criteria for productivity (capacity) of the rolling mill and energy consumption, and ensures rolling condition which would avoid twisting, warping and instability. The algorithm uses the step-back and step-forward procedure. The former means that at every stage the analysis is started from the given shape with known geometrical requirements and thermo-mechanical properties of the material. The latter means that the solution of plasticity boundary problem is performed using the initial shape determined from the step-back.

Nigam [14] has applied interior penalty function method to optimize the various cold rolling parameters for the optimization of total cost in the presence of lubricant. He has chosen roll speed, roll radius, reduction, front and back tensions, and the exit strip speed as the design variables. The effect of roll flattening and high strain rates occurring in rolling phenomenon has also been considered.

Ray [16] proposed a CAPP system for rolling and the work relates to minimization of number of passes to achieve the final product. The principal variables taken are reduction per pass, work-roll and back-up roll diameters for each pass, rolling speed, and tensions at each pass.

Sassani and Sepheri [18] proposed a computer-aided-process planning scheme for multipass variable gap flat rolling of symmetric parts having a smoothly varying cross-section. Three process constraints namely, dynamic constraints (maximum torque available for each pass), the kinematic constraint (the possibility of continuous free rolling) and the convexity constraint (the prespecified draught for the finishing passes) are considered in determining the variation of the roll gap as a function of the rolled length. They developed a numerical algorithm for determining the number and specification of the roling passes required.

Turley [20] proposed a method for determining optimum work-roll size for any cold rolling application. He has proposed different constraints for the selection of optimum roll diameter such as lateral stability, adequate roll cooling, maximum roll separating force etc. and the influence of these constraints has been studied through empirical relationships.

Zhu and Avitzur [21] developed a criterion for the prevention of split ends. The work has been done on the basis of division of the deformation region into a series of triangles undergoing rigid body rotational motions. An upper bound approach has been followed assuming perfectly plastic Mises material.

1.4 Present Work

A review of the existing literature reveals that the computer-aided-process planning has not been extensively used for the planning of process parameters in the rolling operation. Attempts made in this field are related mainly to roll pass design, roll gap analysis etc. No attempt appears to have been made to develop a process plan involving reduction scheduling, tension scheduling etc.

In the present work an attempt has been made to develop a parameter optimization module for the CAPP of tandem cold rolling mill using a combination of variant and generative approaches. The problem is viewed as follows:

Objective Function

1. Minimization of total power.
2. Maximization of production rate.
3. Bi-objective optimization of minimization of total power and maximization of production rate.

Decision Variables

1. Number of stages.
2. Reduction in each stage.
3. Interstand tensions between two consecuitive stages.

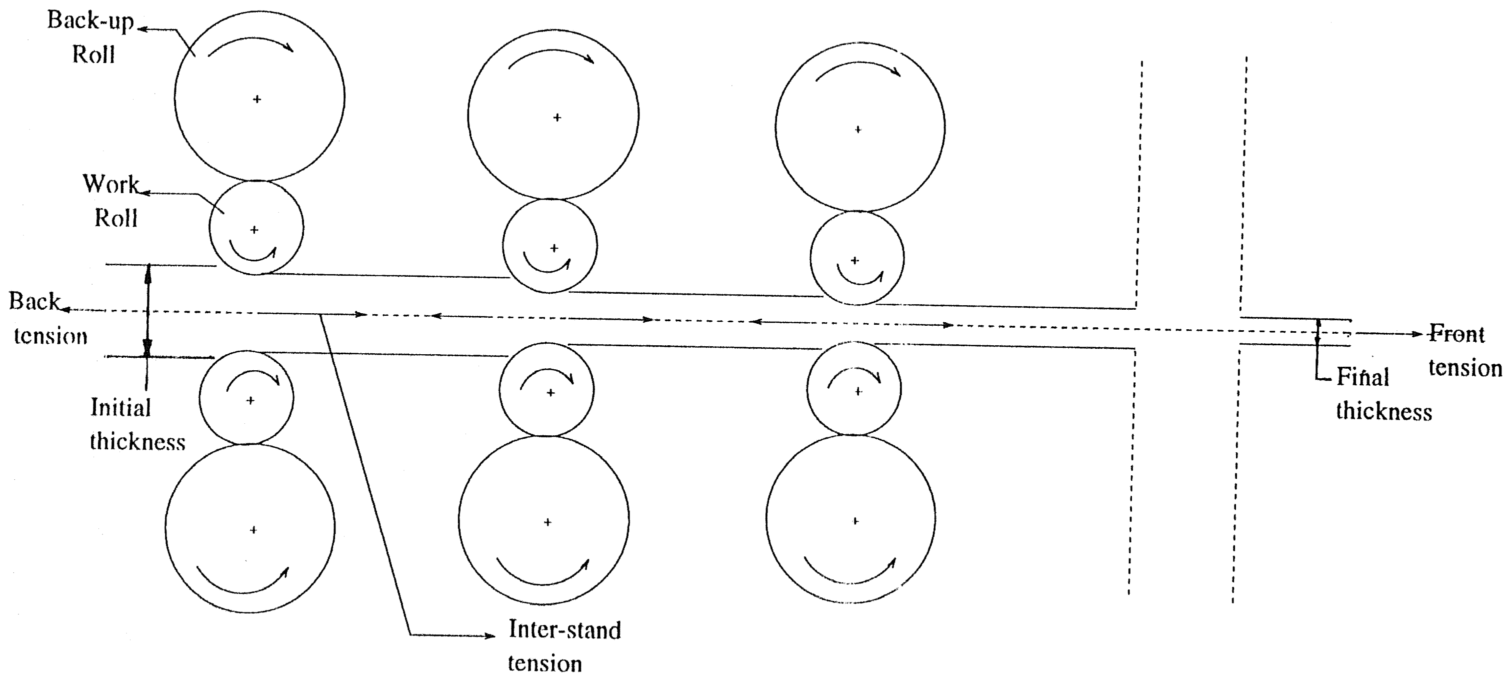


Figure 1.1: Multi-stage cold rolling mill.

4. Velocity of the rolls in each stage.
5. Roll separating force in each stage.
6. Power consumption in each stage.

Constraints

1. Maximum roll velocity for adequate roll cooling.
2. Position of the neutral point to avoid roll skidding.
3. Minimum reduction to avoid side defects.
4. Maximum roll separating force to avoid deflection of the rolls.

The optimization model has been developed using real coded genetic algorithm technique. The general computer program has been taken from Dr. Kalyanmoy Deb, Mechanical Engg. Department, I.I.T. Kanpur.

1.5 Organization of the Thesis

The organization of the thesis report as follows.

Chapter 2 presents the analysis of the system i.e., the basic parameters affecting the performance of the rolling mill, the decision variables and the limitations which have to be imposed while determining the rolling conditions.

Chapter 3 deals with the design of the process planning system involving identification of various inputs, and optimization and evaluation of various process parameters.

Chapter 4 gives the details of the implementation of the proposed system.

Chapter 5 envisages the results for test examples.

Chapter 6 summarizes the conclusion and provides the scope for future work.

Chapter 2

System Analysis

The present chapter discusses various aspects of the rolling process for the purpose of process planning. As stated before, the proposed CAPP system is planned to be designed to achieve anyone or a combination of the proposed objectives (minimization of overall power, maximization of production rate). In the following sections various assumptions, parameters, constraints and objective functions are presented.

2.1 Assumptions

The models used for formulating the process planning problem are based on the following assumptions with respect to strip material and rolling process.

2.1.1 For Strip Material

1. The material is homogeneous, isotropic and plastically incompressible.
2. The flow of the material takes place under isothermal conditions i.e., the effects of temperature changes are negligible.
3. The material obeys von Mises yield criterion and associated flow rule.

2.1.2 For Rolling

1. The deformation of the strip takes place under plane strain conditions i.e., plane section remains plane and deformation of a plane element is homogeneous.
2. The radius of curvature of the deformed roll is uniform across the arc of contact.
3. The thickness of the strip is small as compared to the width.
4. The thickness of the lubricant film is small as compared to the thickness of the outgoing strip.
5. Coefficient of friction is constant over the arc of contact.
6. Effects of strain rate are negligible.

2.2 Decision or Controllable variables

Out of the six decision variables, three (reduction per stage, interstand tension between two consecutive stages, and velocity) are taken as controllable variables and remaining three (number of stages, roll separating force and torque) are treated as process parameters.

1. **Reduction per Stage** (r_i)

   In the rolling operation reduction has a direct influence on power and roll separating force (see eq. 2.8 and eq. 2.19). If the reduction in a stage becomes too high, the roll separating force will increase and may create mill stability problem. If the reduction is too low, the mill efficiency will go down. Therefore, it is very important to have an optimum value of reduction.

   The fractional reduction is the ratio of the draught (reduction in the strip thickness) to the entry thickness of the strip in the stage under consideration, i.e., reduction in i^{th} stage

   $$r_i = \frac{h_{i-1} - h_i}{h_{i-1}} \tag{2.1}$$

where
h_{i-1} : Sheet thickness at the entry of i^{th} stage (m)
h_i : Sheet thickness at the exit of i^{th} stage (m)

2. **Speed of the Rolls (V_{R_i})**

In a rolling mill operation velocity of the rolls plays a very important role. It directly affects consumption of overall power and production rate (see eq. 2.19 and eq. 2.21). If the velocity is too high, there is a possibility of inadequate roll cooling and high power consumption. But if it is too low, then the production rate will go down. Therefore, it is very important to keep the velocity within the optimum range.

3. **Interstand Tensions**

As stated before, in a multi-stage cold rolling mill the sheet is passed through a number of stages to achieve the desired reduction. Interstand tensions are developed during threading operation, when the nose of the strip just reaches the next stand. Interstand tensions developed during the threading operations do continue in the whole rolling operation. If the tension becomes too large, there is a possibility of strip either skidding in the roll gap during threading, or actually tearing. But if it is too low then the looping of the strip may take place. Therefore, it is very important to keep the tension within the optimum limits. The relationships about the range of the interstand tension is given in section 2.5. Interstand tension developed during i^{th} and $(i+1)^{th}$ stage can be calculated as

$$\sigma_{interstand_i} = k_i \times \sigma_{d_i} \tag{2.2}$$

where k_i lies between 0.02 and 0.32 and σ_{d_i} is the yield strength at the i^{th} stage after strain hardening.

2.3 Rolling Parameters

The determination of optimal values of the decision variables has to observe the engineering properties of the workpiece and roll materials. These parameters, referred to as rolling parameters, depend on the shape and size of the workpiece, type of rolling mill, type of lubricant etc. Some of the rolling parameters relevant to the process planning are mentioned below. These are classified into: independent parameters and dependent parameters. Independent rolling parameters are basically related to the properties of the material (e.g. stress-strain characteristics of the sheet material, Young modulus of elasticity of the roll material etc.), whereas dependent rolling parameters (e.g. roll separating force, velocity, etc.) are derived from the independent parameters and are related to the nature of the rolling process.

2.3.1 Independent Rolling Parameters

1. **Stress-Strain Characteristics of the Work Material**

   Rolling is basically a plastic deformation process, depending on the stress-strain characteristics of the work material. Different materials of different grades have different stress-strain characteristics as shown in Table 4.1. Therefore, it is important to know them fairly accurately.

2. **Characterstics of the Roll Material**

   Different type of roll materials have different Young modulus of elasticity. It has a high influence on the decision regarding maximum roll separating force and flattened roll diameter (see eq. 2.7).

2.3.2 Dependent Rolling Parameters

The depending parameters for the process are derived and computed on the basis of the independent parameters. They are as follows:

1. **Coefficient of Friction**

In the cold rolling process, friction along the arcs of contact at the roll-strip interface is necessary for the transmission of deformation energy from the work-rolls to the strip. If the frictional forces are too small, the peripheral speed of the roll will exceed than the exit speed of the strip, or in other words the rolls will skid, whereas larger coefficient of friction will result in a forward or positive slip. In the case of rolling there is always a minimum friction where the two speeds can be closely met. If the frictional effects are considerably in excess of those corresponding to minimum frictional requirements, then the rolling force may become so large that it may lead to roll bending and give the strip a poor shape or inadequate degree of flatness. Therefore, to keep the frictional effects in the optimum range lubricants are used.

Empirically Roberts [17] has established a relationship between the coefficient of friction at a particular stage i and the characteristics of a lubricant. The relationship is function of roll and strip roughness, roll diameter, thickness of strip and roll velocity at that stage and is expressed as

$$\mu_i = \left(\frac{0.8 + 0.7874 q_r}{0.8 + 0.7874 q_s}\right)\left(\sqrt{\frac{h_{i-1} - h_i}{D_w}}\right)\left(0.5 + (k_1 - 0.5)e^{-k_2 V_{R_i}}\right) \tag{2.3}$$

where

D_w	:	Work-roll diameter (m)
K_1	:	First characteristics of the lubricant
K_2	:	Second characteristics of the lubricant $(m/sec)^{-1}$
q_r	:	Roughness of roll (μm)
q_s	:	Roughness of strip (μm)
V_{R_i}	:	Velocity of roll at the i^{th} stage (m/sec)

2. **Yield Strength after Work Hardening**

As the strip is passed in-between the rolls, it is first compressed elastically until it yields, and then it is subjected to plastic deformation

leading to strain hardening of the strip. After the completion of the process the strip gets unloaded.

Yield strength σ_{d_i} in a particular stage i can be calculated as follows [5] [12].

$$\sigma_{d_i} = \sigma_y \left(1 + \frac{e_i}{b}\right)^x \tag{2.4}$$

where b and x are strain hardening coefficients having values as shown in Table 4.1 and e_i is the equivalent strain calculated as

$$e_i = \frac{2}{\sqrt{3}} \ln \frac{h_0}{h_i} \tag{2.5}$$

where

h_0	:	Blank thickness (m)
σ_y	:	Annealed yield strength of the blank (N/m^2)
σ_{d_i}	:	Yield strength after work hardening at i^{th} stage (N/m^2)

3. **Constrained Yield Strength**

Constrained yield strength is the actual rolling pressure in the absence of front and back tensions, that the rolls have to apply on the incoming material to plastically deform it. It has been found to be 1.155 times the strain hardened yield strength [17], i.e.,

$$\sigma_{c_i} = 1.155 \times \sigma_{d_i} \tag{2.6}$$

σ_{d_i} can be calculated from eq. 2.4.

4. **Flattened Roll Diameter**

The work-rolls used in the rolling process can never be perfectly rigid. As a result, they undergo elastic deformation when subjected to roll separating force. Under this condition of deformation the effective roll diameter is taken to be greater than the original roll diameter.

The value of the flattened roll diameter at the i^{th} stage can be calculated as [9]

$$D_{e_i} = D_w \left(1 + \frac{4.61 f_{R_i}}{E h_{i-1} r_i}\right) \tag{2.7}$$

where

D_w	:	Work-roll diameter (m)
E	:	Young modulus of elasticity of the work-roll material (N/m^2)
f_{R_i}	:	Specific roll separating force at the i^{th} stage (N/m)

5. **Roll Separating Force**

Generally the effective coefficient of friction is larger than the minimum permissible value, and the pressure distribution along each arc of contact assumes the form of two exponential curves, as shown in Fig. 2.1. This situation complicates the mathematical model for force, but assuming that the slopes of the hill are linear, some simplification can be done. Roberts [17] has given an empirical relationship for the calculation of specific roll separating force as

$$f_{R_i} = \left(\frac{(\sigma_{c_i} - \sigma_{av_i})}{1 - r_i}\right) L_{R_i}(1 - 1.25 r_i + \frac{\mu_i L_{R_i}}{2h_{i-1}}) \tag{2.8}$$

where L_{R_i} the length of the arc of contact at the i^{th} stage can be calculated as

$$L_{R_i} = \sqrt{0.5 D_{e_i} r_i h_{i-1}} \tag{2.9}$$

The average stress in the strip at i^{th} stage can be calculated as

$$\sigma_{av_i} = \frac{\sigma_{i-1} + (1 - r_i)\sigma_i}{2 - r_i} \tag{2.10}$$

where

σ_{i-1}	:	Back tension at the i^{th} stage (N/m^2)
σ_i	:	Front tension at the i^{th} stage (N/m^2)

In the case of tandem cold rolling mill back tension at the 1^{st} and the front tension at the last stage is taken as zero [3] and the interstand tensions developed between i^{th} and $(i+1)^{th}$ stage acts as front tension for the i^{th} stage and back tension for the $(i+1)^{th}$ stage.

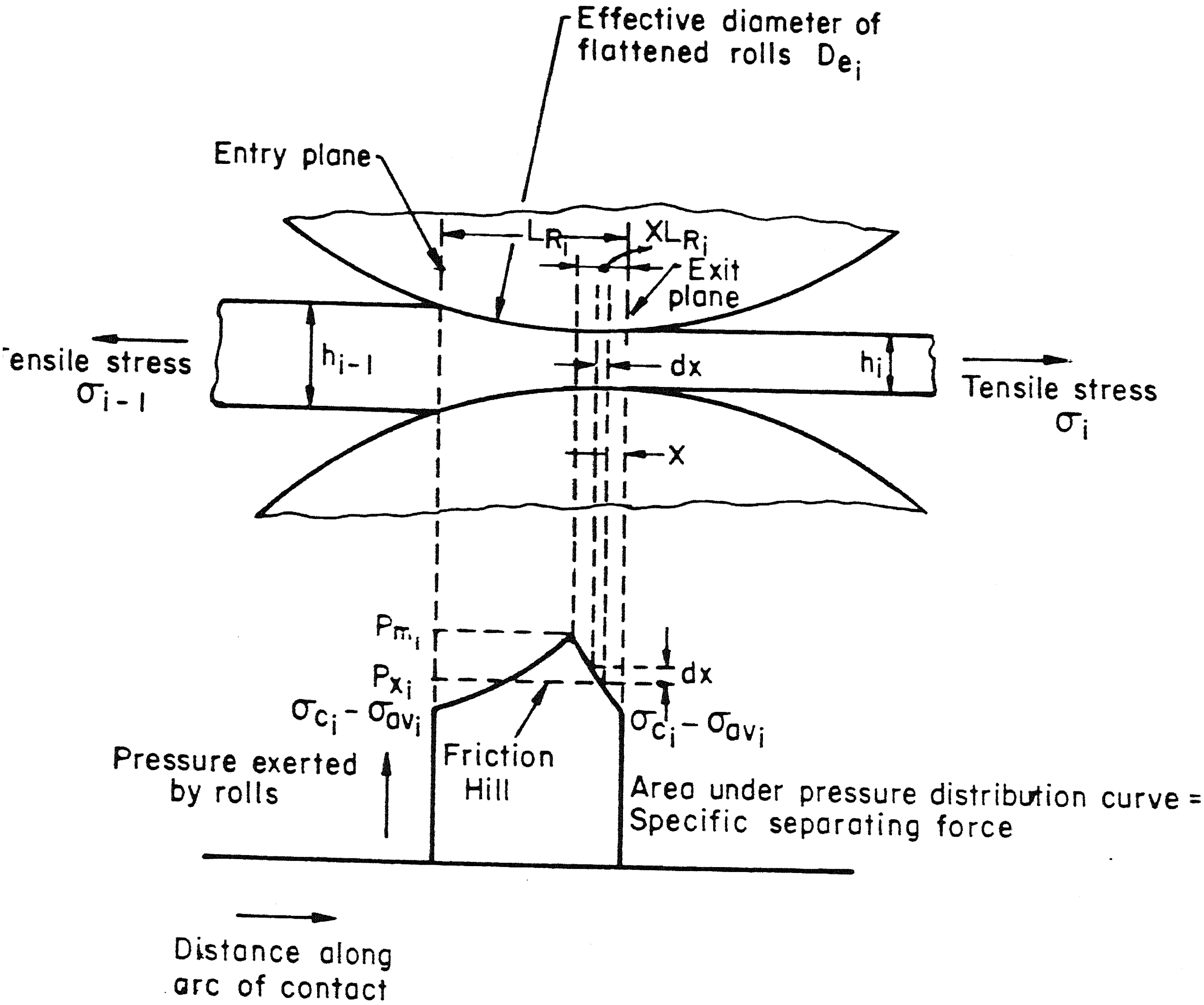


Figure 2.1: Pressure distribution across the arc of contact.

Roll separating force and flattened roll diameter can be calculated by simultaneously solving eqs. 2.7 and 2.8.

6. **Neutral Angle and Slip**

As the strip is plastically deformed in the roll bite, the speed of the strip increases steadily from entry to the exit. On the entry side the rolls move faster than the strip and the frictional forces draw the strip into the rolls.

On the exit side the strip moves faster than the rolls. At some intermediate plane the strip and the rolls move with the same velocity. This plane is known as the neutral plane and the ratio of difference between roll and strip velocity (at the exit) to the roll velocity is known as slip.

The neutral point can be calculated from [4]

$$x_{n_i} = 0.475\left(1 - \left(\frac{0.640}{\mu_i f_{R_i}}(\sigma_{i-1}h_{i-1} - \sigma_i h_i) + \frac{0.54}{\mu_i}\sqrt{\frac{2(h_{i-1}-h_i)}{D_{e_i}}}\right)\right) \tag{2.11}$$

where

$$x_{n_i} = \frac{\phi_{n_i}}{\phi_{b_i}} \tag{2.12}$$

x_{n_i}	:	Non-dimensional neutral angle
ϕ_{n_i}	:	Neutral angle at the i^{th} stage
ϕ_{b_i}	:	Angle of bite at the i^{th} stage

The slip in i^{th} stage can be calculated as [7]

$$f_i = 1 + \frac{x_{n_i}^2(h_{i-1} - h_i)}{h_i} \tag{2.13}$$

7. **Velocity of the Rolls at the Subsequent Stages**

Velocity of the rolls at the subsequent stages can be calculated using volume constancy condition. If in a particular stage neutral point

thickness is h_{n_i} and the velocity of the roll is V_{R_i} then from volume constancy [9]

$$V_{R_i} h_{n_i} = constant \tag{2.14}$$

and

$$h_{n_i} = h_i(1 + f_i) \tag{2.15}$$

2.4 Criterion or Objective

1. **Rolling Power**

For the calculation of specific torque per spindle τ_i Robert [17] has given an empirical relationship,

$$\tau_i = \frac{D_w h_{i-1} r_i}{4} \left(\frac{f_i}{\sqrt{\frac{D_{e_i} h_{i-1} r_i}{2}}} + \sigma_{av_i} \right) \tag{2.16}$$

and the power to apply the interstand tensions at i^{th} stage can be calculated from

$$p_{e_i} = V_{e_i} h_i (\sigma_{i-1} - \sigma_i) \tag{2.17}$$

and the velocity at the exit can be calculated as

$$V_{e_i} = V_{R_i}(1 + f_i) \tag{2.18}$$

Therefore, the total power at stage i can be written as

$$p_i = 2\tau_i \omega_i + p_{e_i} \tag{2.19}$$

where ω_i is the angular velocity of the work-roll at stage i and can be calculated from

$$\omega_i = \frac{V_{R_i}}{0.5 D_w} \tag{2.20}$$

Therefore, for a tandem rolling mill the total power can be evaluated as follows.

Total power= $\sum_{i=1}^{n} p_i$

2. **Production Rate**

Production rate is measured in terms of mass flow rate. In mathematical form it can be written as

$$Production\ rate = \rho h_{n_i} V_{R_i} w \tag{2.21}$$

where
ρ : Density of the sheet material
w : Width of the sheet

3. **Total Cost**

Total Cost=Operating Cost+Lubrication Cost+Electricity Cost
or,

$$Total\ cost = c_1 L + \sum_{i=1}^{n} (c_2 w g_i L_{R_i} + c_3 p_i) \tag{2.22}$$

where
c_1 : Operating cost per unit length of the sheet (Rs/m)
c_2 : Cost of lubricant (Rs/m^3)
c_3 : Cost of power (Rs/W)
g_i : Roll gap at stage i (m)
L_{R_i} : Length of arc of contact at stage i (m)

2.5 Process Constraints

1. **Equality Constraint for Total Reduction**

The total reduction r_t can be expressed in terms of reduction in each stage as

$$r_t = 1 - (1 - r_1)(1 - r_2)(1 - r_3)\ldots(1 - r_n) \tag{2.23}$$

where

$$r_t = \frac{h_0 - h_n}{h_0} \tag{2.24}$$

h_0=Initial blank thickness (m)
h_n=Final thickness of the product (m)

2. **Interstand Tension Constraint**

   Interstand tension should be kept within the permissible range. Too high tension may cause tearing of the strip and too low tension may cause looping of the strip. It has been found [3] that the upper limit is 33% of the yield strength and the minimum is 2% of the yield strength. A proper value can be selected by putting a constraint on the position of the neutral point (as it should remain within the roll bite) and by optimizing the given objecive.

3. **Constraint on the Neutral Point**

   To avoid skidding neutral point must lie within the roll bite, i.e.,

   $$0 \leq x_{n_i} \leq 1 \tag{2.25}$$

   where

   x_{n_i} : Non-dimensional neutral angle at the i^{th} stage

4. **Maximum Roll Separating Force Constraint**

   The separating force developed at any stage is to be kept below a limit determined by the design force of the bearings. Its maximum value can be estimated from [20].

   $$f_{R_{max}} = 9.573 \times 10^6 \times D_b^2/w \tag{2.26}$$

   where

   D_b : Back-up roll diameter (m)
   $f_{R_{max}}$: Maximum Roll separating force (N/m)
   w : Width of the sheet (m)

5. **Constraint on Maximum Roll Velocity**

   To facilitate adequate roll cooling the velocity of the roll must not cross the permissible range as given by [14].

$$V_{max_i} = \frac{13.95(r_i - 2)D_w H(T_{R_i} - T_{c_i})}{h_{i-1} r_i \sigma_{c_i} \ln(1 - r_i)} \tag{2.27}$$

where

H	:	Heat transfer coefficient of the lubricant (W/m^2 °C)
V_{max_i}	:	Maximum velocity of the roll at the i^{th} stage (m/sec)
T_{R_i}	:	Work-roll temperature at the i^{th} stage (°C)
T_{c_i}	:	Temperature of the coolant at the entry of the i^{th} stage (°C)

6. **Constraint for the Prevention of Split Ends or (Alligatoring)**

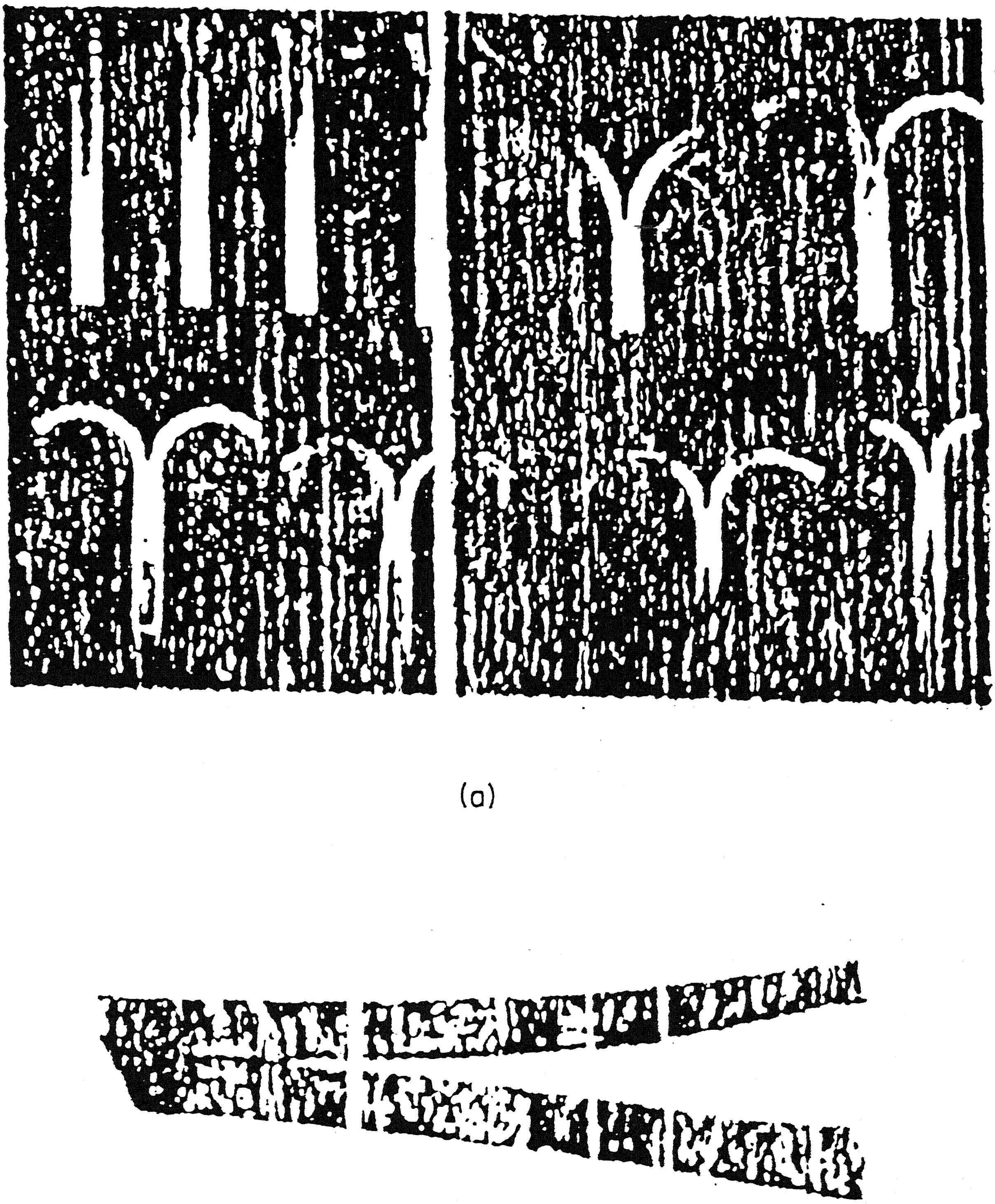
This defect appears usually after severe successive reductions without annealing. The defect initiates as a crack, forming along the central plane of the deformed materials (the plane connecting the axis of symmetry of the rolls). As the rolling proceeds, the two halves of the material separate from each other and alligatoring occurs as shown in Fig. 2.2. Avitzur et. al. [21] in 1988 has shown that to avoid alligatoring the following criterion must be satisfied:

$$\frac{h_{i-1}}{D_w} \leq \left(\frac{h_{i-1}}{h_i} - 1\right) \times 0.905 \tag{2.28}$$

7. **Constraint for the Roll Temperature**

It is very important that the work-roll temperature should not be very high. As excessive temperature may alter the mill crown. This effect tends to be severe with larger rolls. The major effect of the excessive temperature, although probably a function of the strip temperature rather than the roll temperature, is that the surface finish of the strip degrades, in extreme cases causing heat streaks, or friction marks.

Roberts [17] has proposed that the work-roll temperature in case of soluble oil should not exceed 100 °C, persumely to prevent formation of insulating pockets of vapor. For mineral oils, roll temperature may be as high as 130 °C. For the present work the limiting roll



(b)

Figure 2.2: Typical split ends.

temperature has been taken as 110 °C and the oil inlet temperature has been taken 27 °C.

2.6 Solution Methodology

The commom methodology used in process planning is to divide a process into several activities, arranged in such a manner that the required inputs of an activity get linked with the outputs of the other activities. Wherever optimization is needed, objective function and the list of constraints are prepared and an optimal balance between different activities is achieved by some optimization technique.

In the case of CAPP development for the rolling process, there exist several data-bases which interact amongst themselves. The major optimization problem is as stated above. The problem is a non-linear function problem (NLP). There is no special structure of the objective functions and constraints (as in the case of machining, the relationships emerge as posynomial owing to tool life equation). The problem can be solved by using any general method applicable to an NLP. There are some applications of penalty function method as reported, for optimization in case of rolling [14]. The recently emerging methodologies such as tabu search, simulated annealing and genetic algorithm so far do not seem to find a wide applications.

Chapter 3

Design of the Proposed CAPP System

The aim of a CAPP system is to generate the most economical process plan. This task is accomplished by dividing CAPP activities into two phases. One is the design of the system and the other one is implementation. The first phase handles the mathematical procedure and the other phase handles the transformation of the theoretical design into practical ones by the use of available informations. The important aspects of the design are discussed in the present chapter. The implementation aspects have been covered in the next chapter.

The proposed CAPP system comprises of the following modules (or sub-systems):

1. Input to the System
   Various inputs required for different computations are
   - Sheet specifications,
   - Rolling mill specifications,
   - Lubricant specifications,
   - Coolant specifications,
   - Criterion or objective.
2. Evaluation of process parameters.
3. Optimization of decision variables.

4. Process plan output.

The various elements of design are shown in Fig. 3.1.

3.1 Input to the System

3.1.1 Specifications of Sheet

System needs input of the sheet specifications in the form of material, roughness and geometrical data.

- Material Data
  In a rolling process, various relevant mechanical and metallurgical properties (yield strength and strain hardening coefficients etc.) are required for the evaluation of process parameters, objective functions and constraints. These properties are organized and edited in the form of a data base. Such a data base can be suitably updated and edited as per requirement. Selection of a particular material automatically fetches all the data about the material necessary for various computations.

- Geometrical Data
  This includes the
  - Initial blank thickness and the
  - Final desired thickness of the product.

- Surface roughness of the strip

3.1.2 Specifications of Rolling Mill

Next, the following inputs of the mill specifications are needed:

- Work-roll diameter.

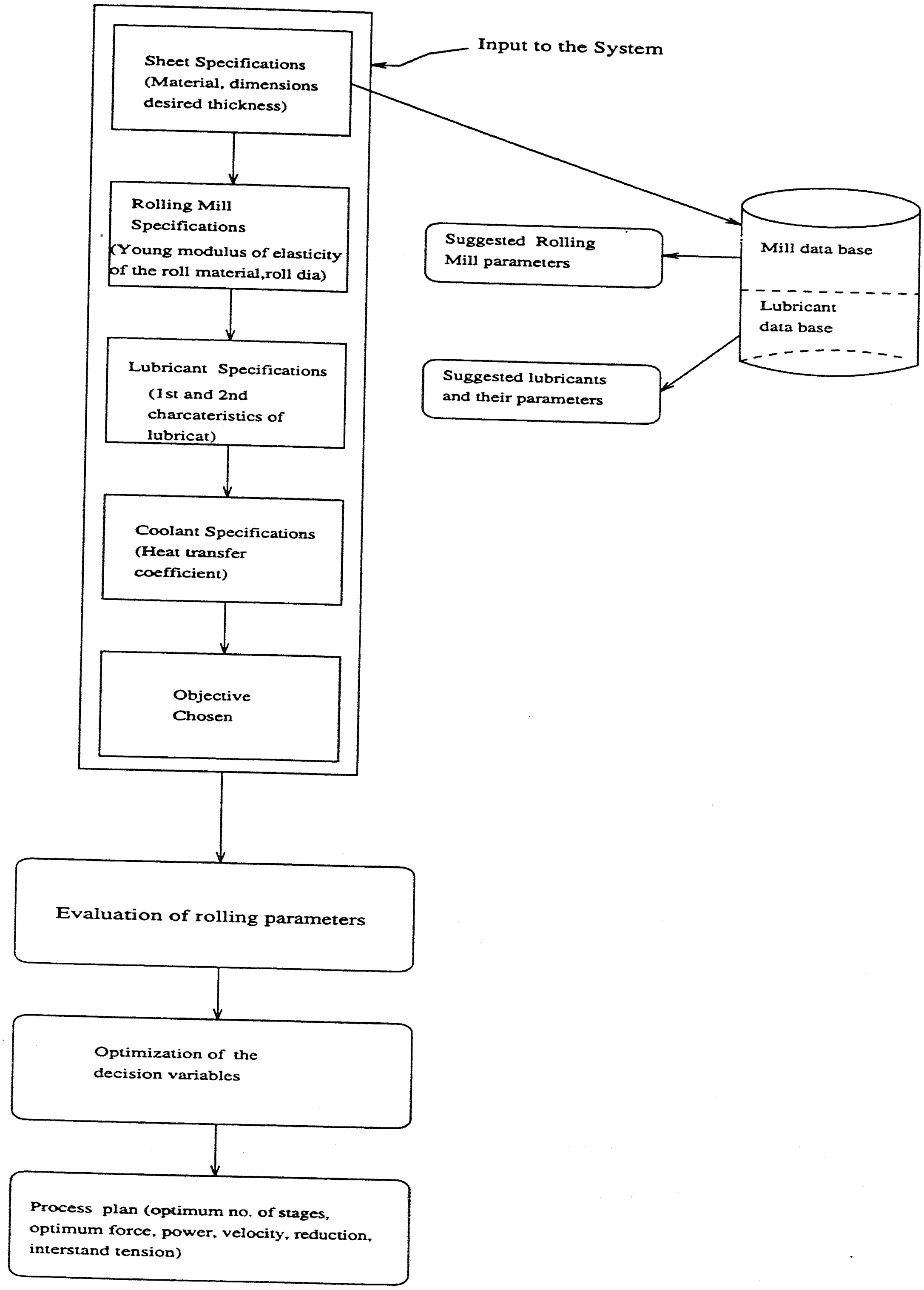


Figure 3.1: System flow chart.

- Back-up roll diameter.
- Young modulus of elasticity of the work-roll material.
- Surface roughness of the work-roll.

3.1.3 Specifications of the Lubricant

In the case of rolling, calculation of friction requires the value of characteristics of the lubricants. A list of lubricants and the approximate values of the characteristics are organized in the form of a data base. Selection of a particular sheet material automatically displays all the data related to the lubricants. The required characteristics are as follows:

- 1^{st} characteristics of the lubricant.
- 2^{nd} characteristics of the lubricant.

3.1.3.1 Specifications of the Coolant

As indicated in section (2.5), the work-roll temperature should not be excessively high and to maintain the temperature in the acceptable range coolants are used. For evaluating the maximum roll velocity (eq. 2.27) the system needs the value of the heat transfer coefficient.

3.1.3.2 Criterion or Objective

For optimization of decision variables, it is very important to specify the objective function. These objective functions have been arranged in the form of a data base. Selection of a particular objective or criterion automatically brings the objective function.

3.2 Evaluation of Process Parameters

Corresponding to the above inputs, the evaluation of different process parameters are carried out. The various relationships used are indicated in Table 3.1.

S.No.	Process parameters	Relatioship used
1	Yield strength after strain hardening	eq.(2.4)
2	Interstand tension	eq.(2.2)
3	Constrained yield strength	eq.(2.6)
4	Roll-separating force	eq.(2.8)
5	Flattened roll diameter	eq.(2.7)
6	Neutral point position	eq.(2.11)
7	Velocity in the subsequent stages	eq.(2.13)
8	Coefficient of friction	eq.(2.3)

Table 3.1: Different relationships used for evaluating process parameters.

The flow chart (Fig. 3.2) summarizes the steps to complete the evaluation of process parameters.

3.3 Optimization of the Decision Variables

In order to carry out the optimization various process parameters are evaluated as shown in Table 3.1. The optimization process requires the number of stages (n) as an input. This is also a design variable in itself (sec.1.5). Therefore, n is initiated with some feasible value and then incremented by one each time and optimization proceeds after interacting with the incremental value of n. In the present system optimization is carried out using real coded genetic algorithm (GA) technique. A brief overview of the GA technique is presented below.

The operation of GA begins with a population of random variables representing the decision variables. Thereafter, each variable is evaluated to find the value of the fitness function. The population is then operated by three main operators: reproduction, cross-over, and mutation to create a new population of points. The new population is further evaluated and tested for termination. This procedure is continued until the termination criterion is met. One cycle

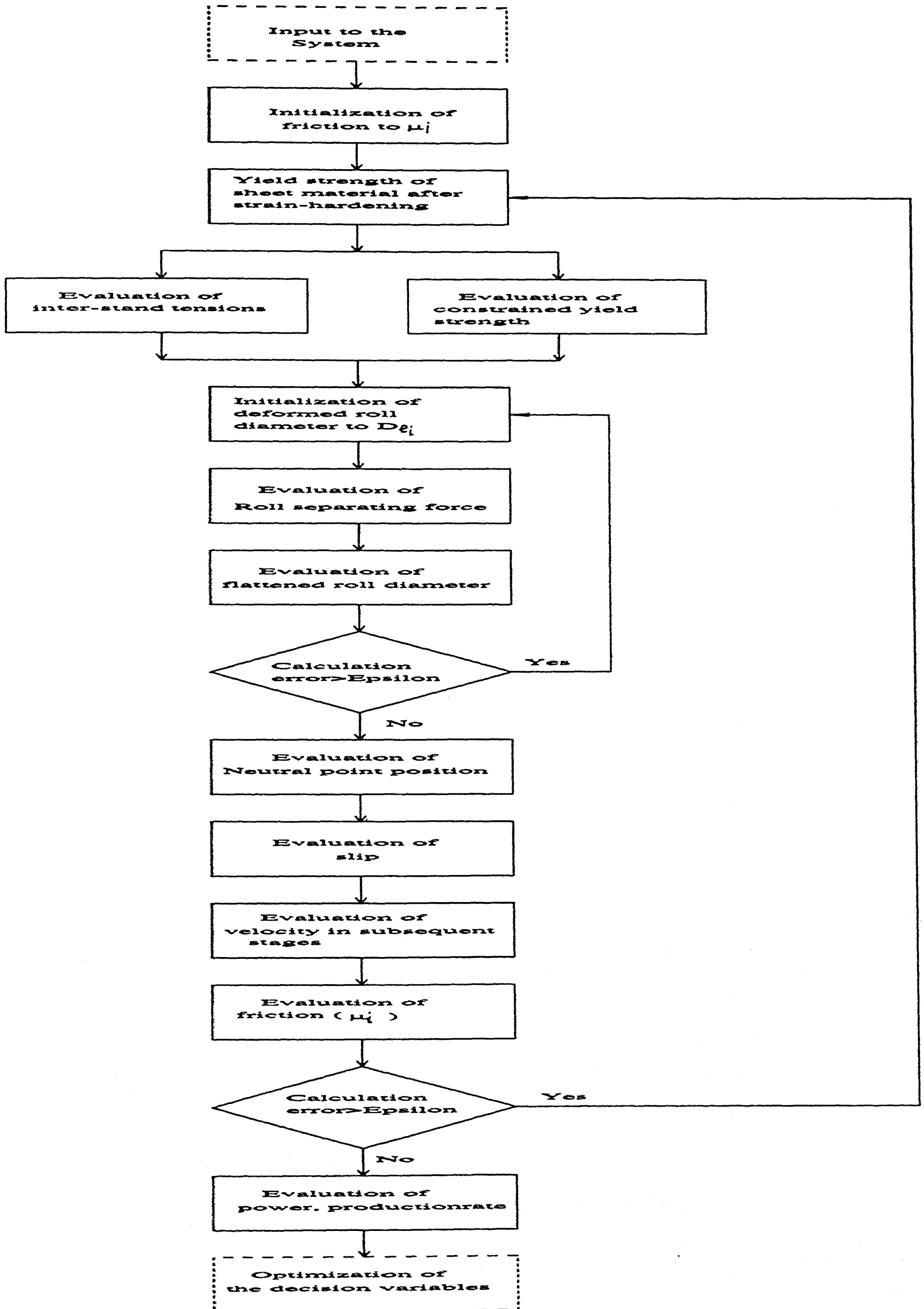


Figure 3.2: Flow chart for the evaluation of process parameters.

of these operators and the subsequent evaluation procedure is known as one generation. The whole operation has been summarized in Fig. 3.3.

Reproduction operator is usually the first operator applied on a population. In the reproduction operator the variables are selected from a population with a probability proportional to the fitness. Multiple copies of these variables are inserted in the mating pool in a probabilistic manner.

In the cross-over operators new variables are created by exchanging information among variables of the mating poll. The percentage of the variables in the cross-over depends on the cross-over probability. If the cross-over probability is p_c, then only $100p_c$ percent of the strings in the population are used in the cross-over.

Mutation operator is used to create a point in the neighbourhood of the current point, thereby achieving a local search around the current solution. The percentage of the variables participating in the mutation depends on the mutation probability. If the mutation probability is p_m then only $100p_m$ percent of the variables participate in mutation.

There are different type of reproduction, mutation and cross-over operators available in the literature but they all work in the same way as mentioned above. The details are available in reference [5].

For the present purpose general optimization program has been taken from Dr. Kalyanmoy Deb, Mechanical Engg. Department, I.I.T. Kanpur. The program has been formulated to solve a minimization problem. Therefore, any maximization problem such as maximization of production rate is first converted into a minimization problem and then solved. The other two objective function related to cost and power are already minimization problems. To take care of the constraints different methods have been suggested, but penalty term are generally used. In general, a fitness function can be written as

$$fit(x) = f(x) + \sum_{j=1}^{J} r_j g_j(x) \tag{3.1}$$

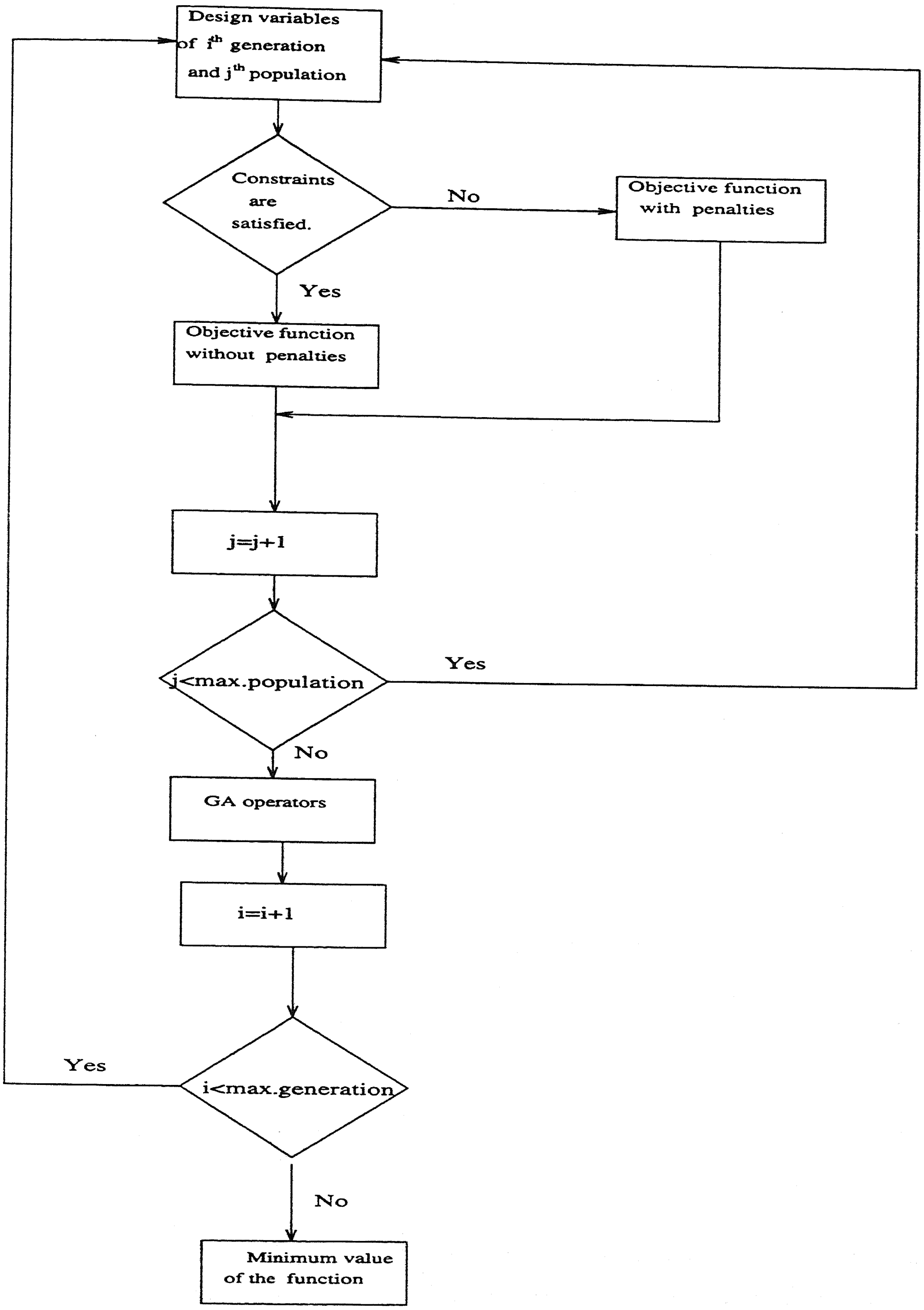


Figure 3.3: Optimization flow chart.

In the above equation $f(x)$ denotes the modified objective function and $\sum_{j=1}^{J} r_j g_j(x)$ denotes the penalty function. In the penalty function $r_j g_j(x)$, r_j denotes the penalty factor and $g_j(x) \geq 0$ denotes the constraint. For a minimization problem, $f(x)$ will be the same as the objective function and for a maximization problem it can be written as

$$f(x) = \frac{1}{1 + objective function} \tag{3.2}$$

For bi-objective optimization of minimum power and maximum production rate the modified objective function can be written as follows.

$$fit(x) = k_1 w_1 f_1(x) + k_2 w_2 f_2(x) \tag{3.3}$$

where, w_1 and w_2 denotes the weightage given to the first and second objective function. And k_1 and k_2 are the scaling factors that are to be multiplied with the 1^{st} and 2^{nd} functions to make their order equal.

In the present analysis penalty terms have been used in the following two different ways:

1. One way is to substitute the fitness function by a very high penalty term (only at the time of violation of the constraint). As already mentioned, GA works on a population of points rather than on a single point. Therefore, in a generation wherever the constraint is violated, the value of the function will be too high and subsequently such points will get eliminated.

2. The other way is to add suitable penalty term to $f(x)$ at the time of violation of the constraint.

The first type of penalty terms has been used where the constraints violation is almost impossible or will take place only in exceptional cases. At other places second type has been used. The penalty terms have been evaluated by trial and error.

The important steps involved for carrying out optimization for a process planning problem are as follows:

- Selection of decision variables.
- Formulation of the modified objective function.
- Formulation of constraints.

3.3.1 Selection of Decision Variables

The formulation of a process planning problem begins with identifying the underlying design variables. A process planning problem usually involves a large number of design parameters of which some are highly sensitive to the proper working of the system. These parameters are called the design variables, and the other parameters usually remain fixed or vary in relation to the design variables. In the present system the following parameters have been chosen as the design variables:

- Reduction in each stage.
- Ratio of interstand tension to the yield strength.
- Velocity of roll in the first stage.

For a n stage problem there will be n reductions and $(n-1)$ interstand tensions. Therefore, total number of variables= $n + (n-1) + 1 = 2n$

3.3.2 Formulation of the Modified Objective Function

Having chosen the design variables the next task is to identify the objectives and the formulation of the modified objective function $f(x)$. The formulation of $f(x)$ depends on the objective chosen for the design of the system. The proposed criterion are

- Maximization of production rate,
- Minimization of overall power,
- Minimization of total cost, and
- Bi-objective optimization of minimization of overall power and maximization of production rate.

For the objective of minimization of overall power, the modified objective function used is

$$f(x) = \sum_{i=1}^{n} p_i \tag{3.4}$$

where power for each stage p_i can be evaluated from eq. 2.19.

For maximization of the production rate, the following form of eq. 2.21 has been used as $f(x)$:

$$f(x) = \frac{1}{1 + V_{R_i} h_{n_i}} \tag{3.5}$$

(As the plastic flow has been assumed to be incompressible under the conditions of plane strain deformation. Therefore, the effect of density and width has not been incorporated in the fitness function).

For minimization of total cost, the following function has been used as $f(x)$:

$$f(x) = total\ cost \tag{3.6}$$

Total cost can be evaluated using eq. 2.22.

For bi-objective optimization of minimization of overall power and maximization of production rate, the following function has been used as $f(x)$:

$$f(x) = 0.5 \times (\sum_{i=0}^{n} p_i + 5 \times 10^6 \frac{1}{1 + V_{R_i} h_{n_i}}) \tag{3.7}$$

where weightage w_1=w_2=0.5, and scaling factor $k_1 = 1$ and $k_2 = 5 \times 10^6$.

3.3.3 Formulation of the Constraints

The most important part of any of the process planning problem is to identify the constraints and to formulate them. The types of constraint have already been discussed in the previous chapter. The formulation of constraints from the optimization point of view is given below.

1. **Constraint on Minimum Reduction**

   The constraint on the minimum reduction has been derived using the split-end criterion. Equation 2.28 can be rewritten as

   $$r_i \geq \frac{h_i}{0.905D_w} \tag{3.8}$$

   and on the violation of this constraint the following penalty terms is used as the fitness function:

   $$pen_1(x) = 1 \times 10^{18}(1+ \mid r_i - i^{th}variable \mid) \tag{3.9}$$

   where 1×10^{18} denotes the penalty factor decided after trial and error and $(i^{th}variable - r_i) \geq 0$ denotes the constraint. In the above penalty term 1 is added to $\mid r_i - i^{th}variable \mid$ to keep the penalty term of the order of 10^{18}.

2. **Maximum Force Constraint**

   If the roll separating force goes beyond a limit then the following penalty term is added to $f(x)$:

   $$g_1(x) = \mid f_{R_i} - f_{R_{max}} \mid \tag{3.10}$$

   where $(f_{R_{max}} - f_{R_i}) \geq 0$ denotes the constraint.

3. **Equality Constraint**

   Equation 2.23 can be rewritten as

   $$r_n = 1 - \frac{1 - r_t}{(1 - r_1)(1 - r_2)\ldots(1 - r_{n-1})} \tag{3.11}$$

The value of reduction in the last stage evaluated by algorithm is compared by the value of r_n. If there is any difference then the penalty term used as the fitness function is

$$pen_2(x) = 1 \times 10^{17}(1+ \mid n^{th}variable - r_n \mid) \qquad (3.12)$$

where 1×10^{17} denotes the penalty factor decided after trial and error and $\mid n^{th}variable - r_n \mid = 0$ denotes the constraint. In the above penalty term 1 is added to $\mid n^{th}variable - r_n \mid$ to keep the penalty term of the order of 10^{17}.

4. **Neutral Point Constraint**

As already been mentioned that the neutral point must remain within the roll bite. Therefore, on the violation of this constraint the following penalty terms are used:
If the neutral point goes out of the entry point i.e., $x_{n_i} > 1$ then the penalty term used as the fitness function is

$$pen_3(x) = 1 \times 10^{14} x_{n_i} \qquad (3.13)$$

where 1×10^{14} denotes the penalty factor decided after trial and error and $x_{n_i} > 1$ denotes the constraint.
If the neutral point goes out of the exit point i.e., $x_{n_i} < 0$ then the following penalty terms are added to $f(x)$:

$$g_2(x) = 5 \times 10^8 \mid x_{n_i} \mid \qquad (3.14)$$

where 5×10^8 denotes the penalty factor decided after trial and error and $x_{n_i} > 0$ denotes the constraint.

5. **Maximum Velocity Constraint**

If the velocity at any of the stage exceeds a limit then the following penalty term are added to $f(x)$:

$$g_3(x) = 2 \times 10^7 \mid V_{R_i} - V_{max_i} \mid \qquad (3.15)$$

where 2×10^7 denotes the penalty factor decided after trial and error and $(V_{max_i} - V_{R_i}) > 0$ denotes the constraint.

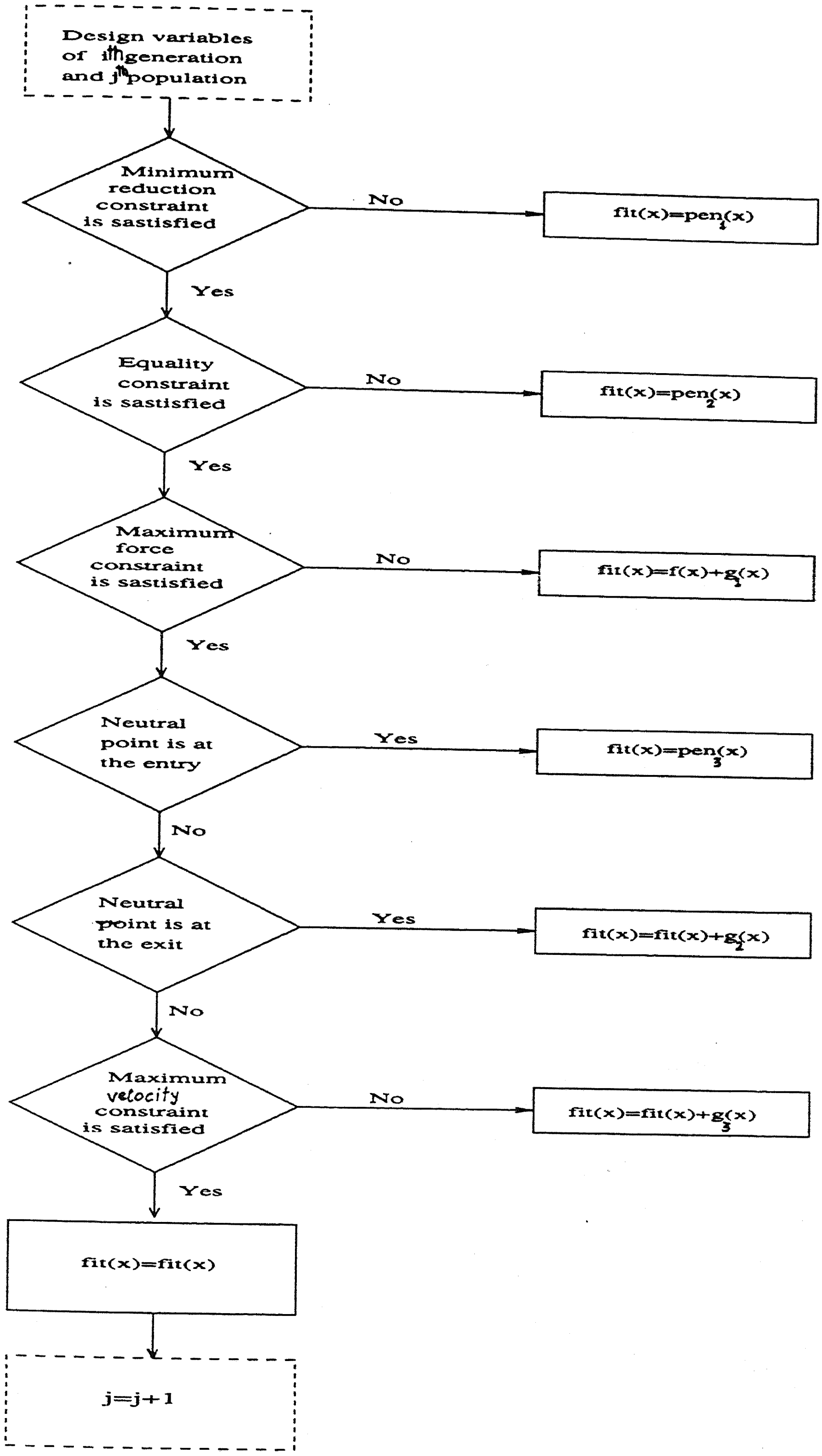


Figure 3.4: Flow chart for the constraints.

3.4 Process plan output

For the above inputs and process parameters a CAPP system for rolling gives the following type of process plan:

INPUTS	
Inputs for	Details
Specification of sheet	**Material data** ... **Geometeric data** •Initial blank thickness(m) ... •Final desired thickness of the product(m) ... **Surface roughness of the sheet**(μm) ...
Specifications of rolling mill	**Work-roll data** • Diameter(m) ... • Surface Roughness (μm) ... •Young-modulus of elasticity(N/m^2) ... **Back-up roll data** •Diameter(m) ...
Specification of Lubricant	1^{st} **characteristics** ... 2^{nd} **characteristics**$(m/sec)^{-1}$ ...
Specifications of Coolant	• Heat transfer coefficient($W/m^{2\circ}C$) ...
Criterion or Objective	...

OUTPUTS					
		Number of stages=...			
Stage	Reduction (%)	Force (N/m)	Velocity (m/sec)	Power (W/m)	Inter-stand tension (N/sqm)
1	...	...	...	...	
					...
2	...	...	...	...	
					...
3	...	...	...	...	
					...
...	...	...	...	...	
					...
...	...	...	...	...	
		Total Power=...			

Chapter 4

System Implementation

As already been mentioned that the implementation phase of process planning deals with the transformation of the theoretical design into practical ones through use of available information. In the case of CAPP these informations are stored in the form of data bases. The information used in the present system are discussed below.

4.1 Selection of Data for Strip Material

The present CAPP system provides the following list of sheet materials to the user:

1. Steel 1
2. Steel 2
3. Aluminium
4. Copper

The user can select any of these materials as per his requirements. The characteristics of these materials are summarized in Table 4.1 in terms of stress-strain relationship of the form eq. 2.4. Here b and x are strain-hardening coefficients and σ_y is the yield strength of the material [15].

Material	σ_y (N/m^2)	b	x
Steel 1	3.24×10^8	0.052	0.295
Steel 2	3.58×10^8	0.044	0.300
Aluminium	5.03×10^7	0.050	0.260
Copper	7.03×10^7	0.022	0.490

Table 4.1: Characteristics of different materials.

4.2 Selection of Roll Parameters

The important roll parameters in a 4-high cold rolling mill are

- Work-roll diameter
- Back-up roll diameter
- Material of work-roll
- Material of back-up roll

The present CAPP system provides guidance to the user for selecting the roll diameters and roll materials. The range of diameters can be selected as [10]

$$0.25L \leq Dw \leq 0.4L$$
$$0.4L \leq Db \leq 0.76L$$

where L=(w+a), w being the width of sheet to be rolled and

$$a = \begin{cases} 0.1m & \text{if } 400 \leq w \leq 1200 \\ 0.35m & \text{otherwise} \end{cases}$$

There is no set rule for the selection of roll material, but is generally decided on the following consideration:

- If the mechanical stress is very high, steel rolls, mainly with low carbon steels, are used.

- If the mechanical stress is moderate, any type of the steel rolls or even cast iron rolls may be used.
- If the mechanical stress is low, any type of rolls including cast iron rolls may be used.

For guidance a list of roll materials (Table 4.2) corresponding to the choice of sheet material is provided to the user [19].

Sheet material	Back-up roll material	Work-roll material
Steel	Forged Steel(55/70 Shore) Cast Steel(<70 Shore) Chilled Cast Iron	Forged Steel(100 Shore)
Copper	Forged Steel(80/90 Shore) Cast Steel (< 70 Shore)	Forged Steel (100 Shore)
Aluminium	Forged Steel(80/90 Shore) Cast Steel (< 70 Shore)	Forged Steel (100 Shore) Flake graphite Cast Iron(>80 Shore

Table 4.2: Roll materials generally used in 4-high cold rolling mills.

4.3 Selection of Lubricant

Typical lubricants used in rolling are summarized in Table 4.3 [13].

Material	Lubricants
Aluminium	Fatty acid+Mineral oil, Polymer emulsion+Synthetic solutions, Mineral oil+Fatty compounds.
Copper	Emulsions, Soap Mineral oil+Fatty acids
Steel 1	Emulsions, Compound oil, Synthetic solutions
Steel 2	Chlorinated parafins+Emulsions Chlorine additives Paraffin+ Mineral oil

Table 4.3: Typical lubricants used in the cold rolling practice.

The value of first and second characteristics (K_1 and K_2) of the lubricants differ significantly. In practice lubricants having K_1 value in excess of unity

and K_2 in the range of $0.0984(m/sec)^{-1}$ to $0.3937(m/sec)^{-1}$ are generally used [17]. The lubricants listed in Table 4.3 have values of k_1 and K_2 in the recommended range.

4.4 Selection of the Objective Function

The present CAPP system provides the following list of the objectives:

1. Minimization of overall power
2. Maximization of production rate
3. Bi-objective optimization of minimization of overall power and maximization production rate by giving equal weightage.

The user can select any of these objectives as per his requirements. The equations for these objectives have been summarized in Table 4.4.

Choice	Equation used
1	eq. 3.4
2	eq. 3.5
3	eq. 3.7

Table 4.4: Different relationships used for the calculation of the objective function.

4.5 Decision on Number of Stages

The present system also deals with the decision regarding the number of stages for a given type of tandem cold rolling mill. Generally, the number of stages are varied from 4 to 6 or 4-7 but in the present system they have been varied from 4 to 7.

In practice, the decision on number of stages to be used is not simple. Increase in the number of stages leads to higher and higher operating cost, but improves the product quality. The decision regarding number of stages,

therefore, requires detailed and comprehensive study. In the present CAPP system the number of stages have been selected on the basis of minimum power for simplified objectives such as minimum power, maximum production rate, or a combination of both. It can provide only a guideline in selecting the number of stages. To support the user in taking the decision the proposed system provides the process plan when the number of stages are varied from 4 to 7.

4.6 Selection of GA Parameters

The important GA parameters are

- Number of maximum generations
- Size of the population
- Cross-over probability
- Mutation probability

In the present system the last two parameters have been fixed at 0.9 and 0.1 values respectively and iterations have been carried out by varying the generation number, and population size. The parameters have been compared on the basis of CPU time and the final value of the fitness function. The selection of these parameters depends on the input to the system, therefore it is difficult to define a common value.

By varying the number of maximum generations and population size this was seen:

- If the total reduction is less than or equal to 55%, the following values can give optimum results:

Maximum number of generations	=	500
Population size	=	500
Cross-over probability	=	0.9
Mutation probability	=	0.1

- If the total reduction is more than 55%, the following values can give optimum results:

Maximum number of Generations	=	800
Population size	=	3000
Cross-over probability	=	0.9
Mutation probability	=	0.1

4.6.1 Illustration

The iterations have been carried out on the following data:

Back-up roll diameter	=	1.2 m
Work-roll diameter	=	0.7 m
Young modulus of elasticity	=	4.56×10^{11} N/m^2
Material to be rolled	=	Steel 1
Blank thickness	=	3 mm
Blank width	=	1.6 m
Heat transfer coefficient of the coolant	=	1730.245 $W/m^{2\circ}C$
First characteristics of the lubricant	=	1.5
Second characteristics of the lubricant	=	0.2953 $(m/sec)^{-1}$
Criterion	:	Minimization of overall power

The some of the important results are as follows:

Total reduction=45%		
Total stages	Value of the fitness function	CPU time
4	3.61043×10^6	7minutes 23.82sec
5	3.62091×10^6	
6	3.65543×10^6	
7	3.65345×10^6	

Table 4.5: Value of fitness function for 500 generations, 500 population size.

Total reduction=50%		
Total stages	Value of the fitness function	CPU time
4	4.25754×10^6	7minutes 33.68sec
5	4.23352×10^6	
6	4.40091×10^6	
7	4.40539×10^6	

Table 4.6: Value of fitness function for 500 generations, 500 population size.

Total reduction=55%		
Total stages	Value of the fitness function	CPU time
4	4.86784×10^6	7minutes 50.22sec
5	4.90889×10^6	
6	5.16595×10^6	
7	5.13356×10^6	

Table 4.7: Value of fitness function for 500 generations, 500 population size.

Total reduction=45%		
Total stages	Value of the fitness function	CPU time
4	3.63993×10^6	5minutes 58.3sec
5	3.59977×10^6	
6	3.77567×10^6	
7	3.70528×10^6	

Table 4.8: Value of fitness function for 500 generations, 400 population size.

Total reduction=50%		
Total stages	Value of the fitness function	CPU time
4	4.18835×10^6	6minutes 9.3sec
5	4.15897×10^6	
6	4.39105×10^6	
7	4.45165×10^6	

Table 4.9: Value of fitness function for 500 generations, 400 population size.

Total reduction=55%		
Total stages	Value of the fitness function	CPU time
4	4.87460×10^6	6minutes 18.26sec
5	4.97440×10^6	
6	5.10305×10^6	
7	5.12811×10^6	

Table 4.10: Value of fitness function for 500 generations, 400 population size.

Total reduction=45%		
Total stages	Value of the fitness function	CPU time
4	3.60867×10^6	9 minutes 10.43sec
5	3.61881×10^6	
6	3.60010×10^6	
7	3.76109×10^6	

Table 4.11: Value of fitness function for 500 generations, 600 population size.

Total reduction=50%		
Total stages	Value of the fitness function	CPU time
4	4.22733×10^6	9minutes 15.65sec
5	4.23405×10^6	
6	4.27444×10^6	
7	4.36151×10^6	

Table 4.12: Value of fitness function for 500 generations, 600 population size.

Total reduction=55%		
Total stages	Value of the fitness function	CPU time
4	4.22733×10^6	9minutes 15.65sec
5	4.23405×10^6	
6	4.27444×10^6	
7	4.36151×10^6	

Table 4.13: Value of fitness function for 500 generations, 600 population size.

Total reduction=60%		
Total stages	Value of the fitness function	CPU time
4	5.75421×10^6	91minutes 8.4sec
5	5.62187×10^6	
6	5.95357×10^6	
7	6.27335×10^6	

Table 4.14: Value of fitness function for 800 generations, 3000 population size.

Total reduction=65%		
Total stages	Value of the fitness function	CPU time
4	6.85301×10^6	96minutes 20.45sec
5	6.63489×10^6	
6	6.71362×10^6	
7	7.24025×10^6	

Table 4.15: Value of fitness function for 800 generations, 3000 population size.

Total reduction=60%		
Total stages	Value of the fitness function	CPU time
4	5.76229×10^6	77minutes 33.47sec
5	5.62944×10^6	
6	5.96223×10^6	
7	6.62982×10^6	

Table 4.16: Value of fitness function for 700 generations, 3000 population size.

Total reduction=65%		
Total stages	Value of the fitness function	CPU time
4	6.85833×10^6	87minutes 56.62sec
5	6.63834×10^6	
6	6.76901×10^6	
7	7.49006×10^6	

Table 4.17: Value of fitness function for 700 generations, 3000 population size.

Total reduction=50%		
Total stages	Value of the fitness function	CPU time
4	4.06829×10^6	10 hrs 24minutes 29.82sec
5	4.12828×10^6	
6	4.22272×10^6	
7	4.35587×10^6	

Table 4.18: Value of fitness function for 5000 generations, 4000 population size.

Total reduction=60%		
Total stages	Value of the fitness function	CPU time
4	5.60740×10^6	10 hr 51minutes 47.19sec
5	5.57508×10^6	
6	5.83832×10^6	
7	5.90021×10^6	

Table 4.19: Value of fitness function for 5000 generations, 4000 population size.

Chapter 5

Results and Discussion

The present CAPP system has been designed and implemented by using the concepts mentioned in the previous chapters. A computer program has been developed on ANSI C complier. The present chapter is concerned with demonstrating the capabilities of the system.

The capabilities of the present system can be examined by varying the different parameters in the prescribed ranges. For the present discussion, the system has been analysed for different objectives while keeping the other parameters constant.

The sample data chosen are as follows:

Back-up roll diameter	=	1.3 m
Work-roll diameter	=	0.7 m
Roughness of the work-roll surface	=	0.5 μm
Young Modulus of Elasticity of the roll material	=	2.5×10^{11} N/m^2
Material to be rolled	=	Steel 1
Blank thickness	=	3 mm
Product thickness	=	1.5 mm
Blank width	=	1.5 m
Roughness of the sheet surface	=	0.5 μm
Heat transfer coefficient of the coolant	=	2000 W/m^2 $^{\circ}C$
First characteristics of the lubricant	=	1.5
Second characteristics of the lubricant	=	0.2 $(m/sec)^{-1}$

Using the above data the CAPP system analyses the parameters in the following six steps.

Step 1

In the first step system takes the sheet data as

Choice of material (Steel 1, Steel 2, Copper, Aluminium, other) :
Thickness of the blank (m) :
Thickness of final product (m) :
Width of the sheet (m) :
Roughness of the sheet (μm) :

Step 2

In the second step the system displays a list of roll materials corresponding to the sheet material and asks the user to enter the Young modulus of elasticity for the work-roll material as

Young Modulus of the Work-roll material (N/m^2) :

The list of roll material is stored as

Roll type	Material
Work-Roll	Forged Steel (100shore)
Back-up Roll	Forged Steel (55/70 shore)
	Cast Steel (<70shore)
	Chilled Cast Iron

Step 3

In the third step the system provides a range of roll diameters and asks the user to enter the roll diameters and surface roughness as

Back-up roll diameter (m) :
Work-roll diameter (m) :
Roughness of the roll (μm) :

The suggested range of diameters are given below :

Roll type	Max. dia(m)	Min. dia(m)
Work-roll	0.740	0.4625
Back-up roll	1.460	0.7400

Step 4

In the next step the system provides a list of lubricants and a general range of 1^{st} and 2^{nd} characteristics corresponding to the sheet material. User is asked to enter the value of 1^{st} and 2^{nd} characteristics for his lubricant as

1st characterstics of the lubricant :
2nd characterstics of the lubricant $((m/sec)^{-1})$:

The recommended lubricants are

1. Emulsions
2. Compound oil
3. Synthetic solutions

Step 5

In this step the system asks the user to enter the heat transfer coefficient of the coolant as

Heat-transfer coefficient of the coolant ($\mathbf{W}/m^{2\circ}C$):

Step 6

In the last step the system provides a list of the proposed objectives and asks the user to select one of these objectives.

Criterion of Optimization :

1. Minimization of power
2. Maximization of production rate
3. Bi-objective optimization of minimization of overall power and maximization of production rate by giving them equal weightage

5.1 Discussion

The results obtained for the test example by varying the objective function have been summarized in Tables 5.1 to 5.12. Some of the results obtained

are also shown graphically in Figs. 5.1 to 5.9 . These show the distribution of reduction over various stages and the variation of roll separating force and overall power with number of stages. Results plotted in these figures show that there is no particular trend of the distribution of reduction. It might be due to the complexity of the constraints and objective functions. For minimization of overall power, the reduction in the first stage is maximum (Fig. 5.1, Tables 5.1 to 5.4) whereas for maximization of production rate reduction in first stage is minimum (Fig. 5.4, Tables 5.5 to 5.8). Power consumption also increases for maximum production rate because of direct influence of velocity on power and production rate. Power variation with number of stages for the first case (minimization of overall power) is not significant, whereas for the second case (maximization of production rate) a significant variation is obtained.

A some what more uniform trend in reduction values is obtained (Fig. 5.7, Tables 5.9 to 5.12) when optimization is carried out with equal weightage to power and production rate. Here the results are closer to that obtained for minimum power. The variation in overall power with increasing number of stages is not very significant.

Stage No.	Reduction (%)	Force (N/m)	Velocity (m/sec)	Power (W/m)	Inter-stand tension (N/m^2)
1	20.44	1.46×10^7	3.00	1.34×10^6	
					1.15×10^7
2	14.53	1.34×10^7	3.52	8.92×10^5	
					1.26×10^7
3	15.02	1.45×10^7	4.14	1.00×10^6	
					1.27×10^7
4	13.20	1.44×10^7	4.77	1.10×10^6	
Total power=4.33 $\times 10^6$W/m					

Table 5.1: Process parameters for 4 stage mill for minimization of overall power.

Stage No.	Reduction (%)	Force (N/m)	Velocity (m/sec)	Power (W/m)	Inter-stand tension (N/m^2)
1	20.44	1.46×10^7	3.00	1.34×10^6	
					1.19×10^7
2	8.92	1.05×10^7	3.30	4.88×10^5	
					1.27×10^7
3	11.84	1.27×10^7	3.75	7.27×10^5	
					1.34×10^7
4	12.78	1.37×10^7	4.29	8.41×10^5	
					1.35×10^7
5	9.98	1.30×10^7	4.78	8.61×10^5	
Total power=4.26 $\times 10^6$W/m					

Table 5.2: Process parameters for 5 stage mill for minimization of overall power.

Stage No.	Reduction (%)	Force (N/m)	Velocity (m/sec)	Power (W/m)	Inter-stand tension (N/m^2)
1	16.75	1.25×10^7	3.00	1.07×10^6	
					1.07×10^7
2	9.47	1.04×10^7	3.33	5.54×10^5	
					1.31×10^7
3	5.87	9.15×10^6	3.53	3.29×10^5	
					1.36×10^7
4	9.33	1.15×10^7	3.90	5.79×10^5	
					1.41×10^7
5	12.15	1.33×10^7	4.43	8.24×10^5	
					1.42×10^7
6	11.27	1.36×10^7	5.00	1.01×10^6	
		Total power=4.37×10^6W/m			

Table 5.3: Process parameters for 6 stage mill for minimization of overall power.

Stage No.	Reduction (%)	Force (N/m)	Velocity (m/sec)	Power (W/m)	Inter-stand tension (N/m^2)
1	14.27	1.11×10^7	3.01	9.25×10^5	
					1.18×10^7
2	6.85	8.69×10^6	3.24	3.66×10^5	
					1.26×10^7
3	6.30	8.98×10^6	3.46	3.44×10^5	
					1.26×10^7
4	7.83	1.03×10^7	3.75	4.79×10^5	
					1.36×10^7
5	14.31	1.41×10^7	4.38	1.03×10^6	
					1.49×10^7
6	3.26	8.89×10^6	4.53	2.08×10^5	
					1.51×10^7
7	12.38	1.40×10^7	5.17	1.16×10^6	
		Total power=4.50×10^6W/m			

Table 5.4: Process parameters for 7 stage mill for minimization of overall power.

Optimum number of stages= 5

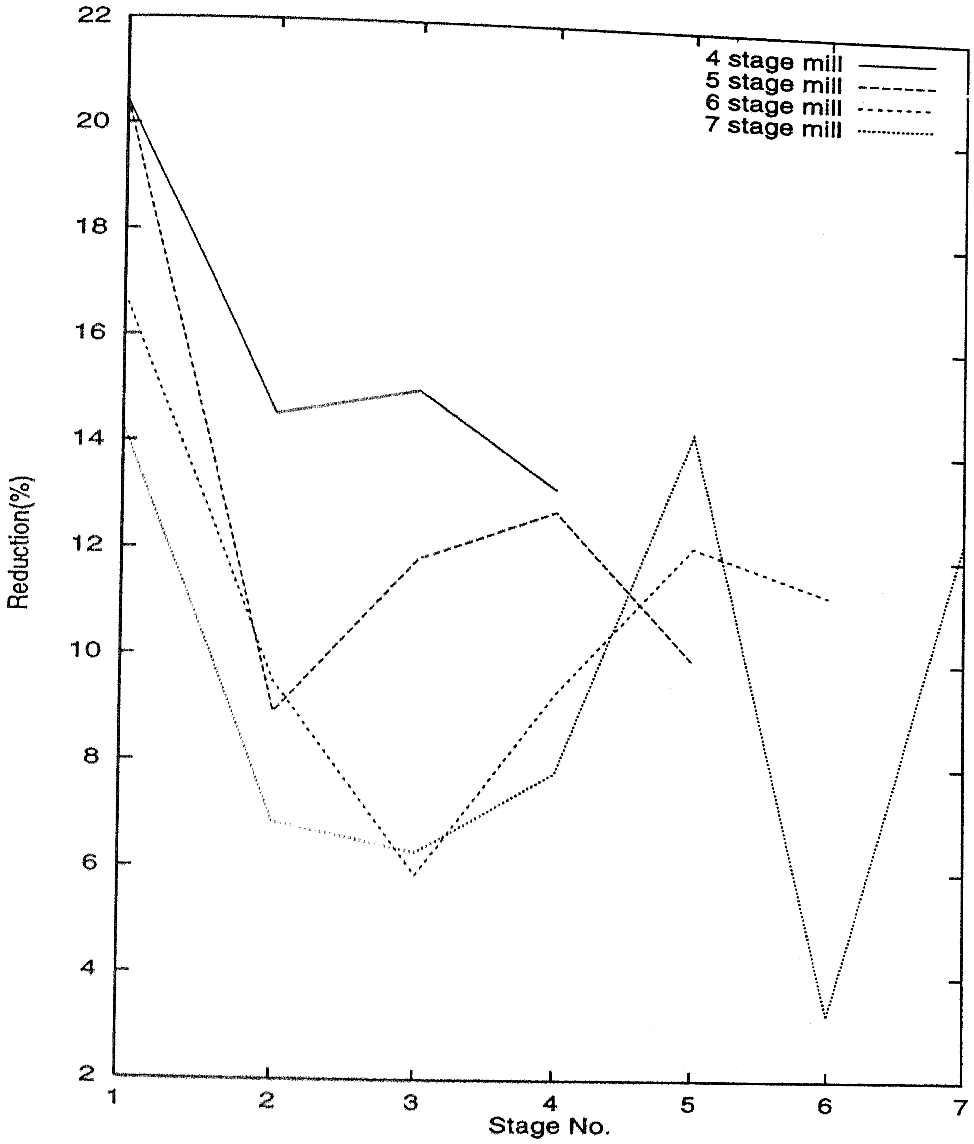


Figure 5.1: Distribution of reduction over various stages for minimization of power.

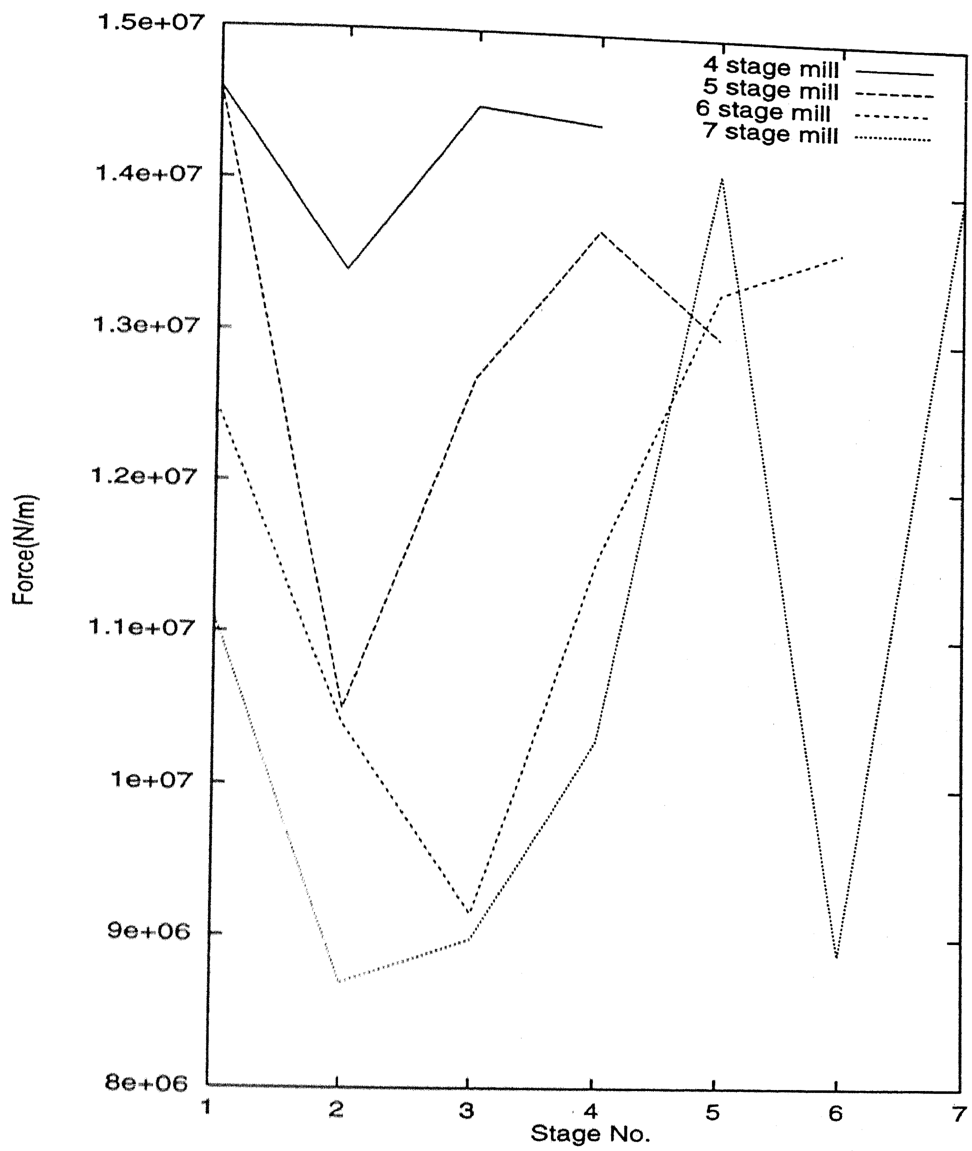


Figure 5.2: Variation of roll-separating force over various stages for minimization of power.

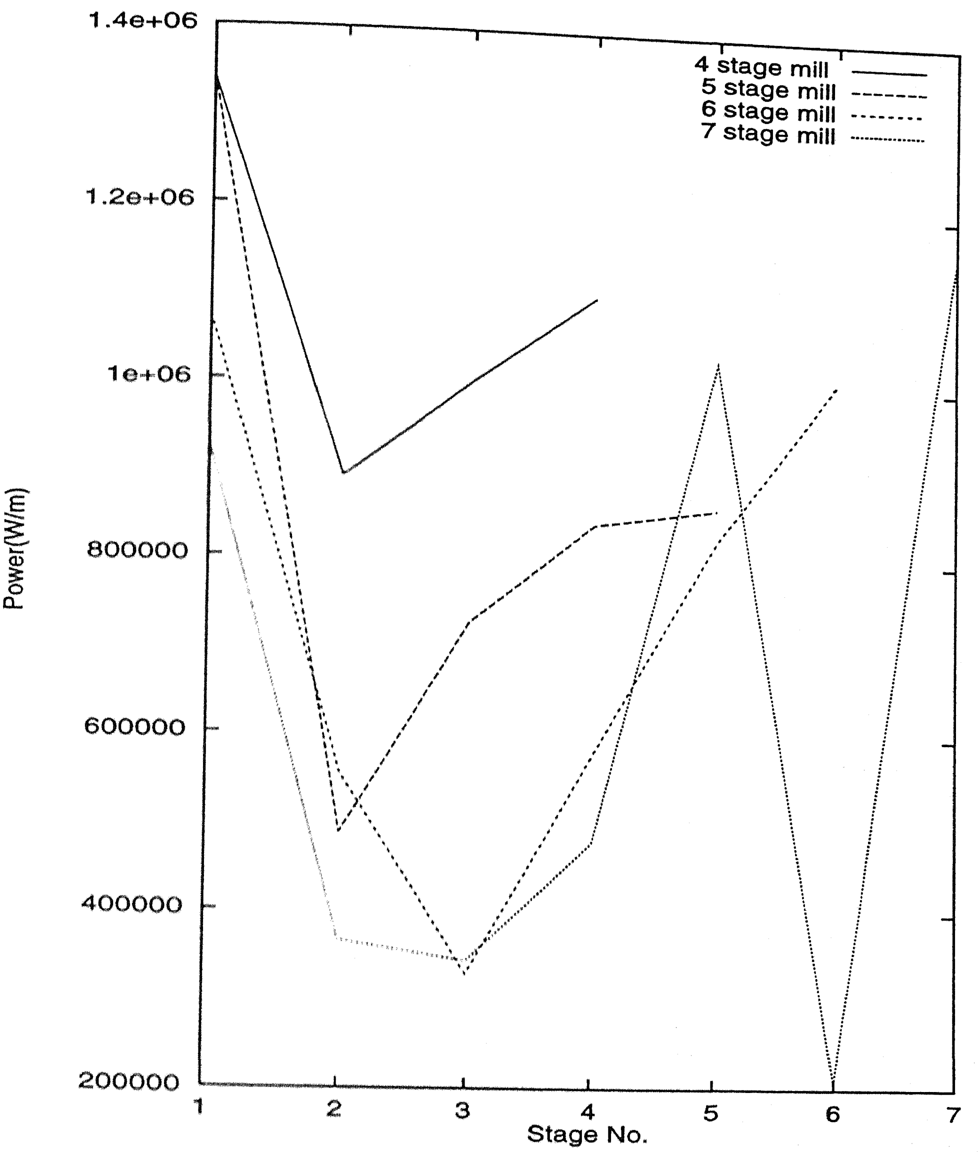


Figure 5.3: Variation of power over various stages for minimization of power.

Stage No.	Reduction (%)	Force (N/m)	Velocity (m/sec)	Power (W/m)	Inter-stand tension (N/m^2)
1	5.26	5.43×10^6	6.00	2.37×10^6	
2	23.01	1.46×10^7	8.06	3.88×10^6	5.50×10^7
3	19.23	1.51×10^7	9.98	3.86×10^6	4.15×10^7
4	14.90	1.45×10^7	11.73	3.29×10^6	2.15×10^7
		Total power=1.34×10^7W/m			

Table 5.5: Process parameters for 4 stage mill for maximization of production rate.

Stage No.	Reduction (%)	Force (N/m)	Velocity (m/sec)	Power (W/m)	Inter-stand tension (N/m^2)
1	4.99	5.26×10^6	6.00	2.24×10^6	
2	11.96	9.40×10^6	7.04	1.53×10^6	5.19×10^7
3	15.88	1.28×10^7	8.36	2.99×10^6	4.66×10^7
4	16.76	1.45×10^7	10.06	3.10×10^6	2.54×10^7
5	14.45	1.45×10^7	11.75	2.97×10^6	1.45×10^7
		Total power=1.28×10^7W/m			

Table 5.6: Process parameters for 5 stage mill for maximization of production rate.

Stage No.	Reduction (%)	Force (N/m)	Velocity (m/sec)	Power (W/m)	Inter-stand tension (N/m^2)
1	5.05	5.32×10^6	6.00	2.26×10^6	
					5.25×10^7
2	11.43	9.17×10^6	7.00	1.58×10^6	
					4.37×10^7
3	9.04	9.41×10^6	7.69	1.50×10^6	
					3.23×10^7
4	10.81	1.13×10^7	8.63	2.08×10^6	
					1.56×10^7
5	14.95	1.39×10^7	10.15	2.51×10^6	
					1.93×10^7
6	13.84	1.42×10^7	11.77	3.01×10^6	
		Total power=1.29×10^7W/m			

Table 5.7: Process parameters for 6 stage mill for maximization of production rate.

Stage No.	Reduction (%)	Force (N/m)	Velocity (m/sec)	Power (W/m)	Inter-stand tension (N/m^2)
1	5.48	5.86×10^6	5.99	1.09×10^6	
					1.85×10^7
2	13.38	1.09×10^7	6.95	1.63×10^6	
					2.05×10^7
3	5.80	8.24×10^6	7.38	6.66×10^5	
					2.04×10^7
4	6.83	9.19×10^6	7.92	1.16×10^6	
					2.98×10^7
5	15.76	1.39×10^7	9.40	2.71×10^6	
					2.02×10^7
6	4.06	9.05×10^6	9.80	6.41×10^5	
					2.92×10^7
7	13.71	1.41×10^7	11.35	3.01×10^6	
		Total power=1.09×10^7W/m			

Table 5.8: Process parameters for 7 stage mill for maximization of production rate.

Optimum number of stages=7

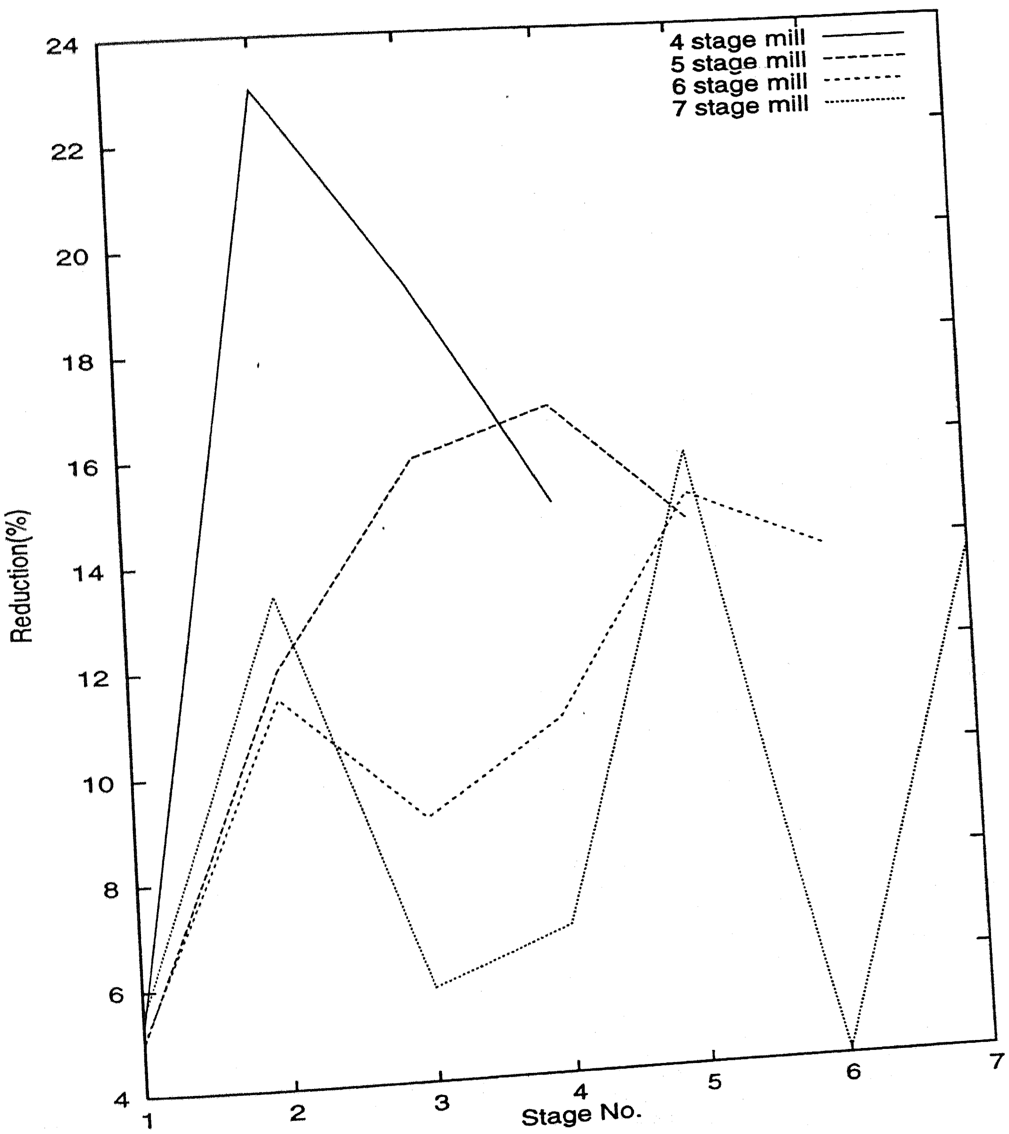


Figure 5.4: Distribution of reduction over various stages for maximization of production rate.

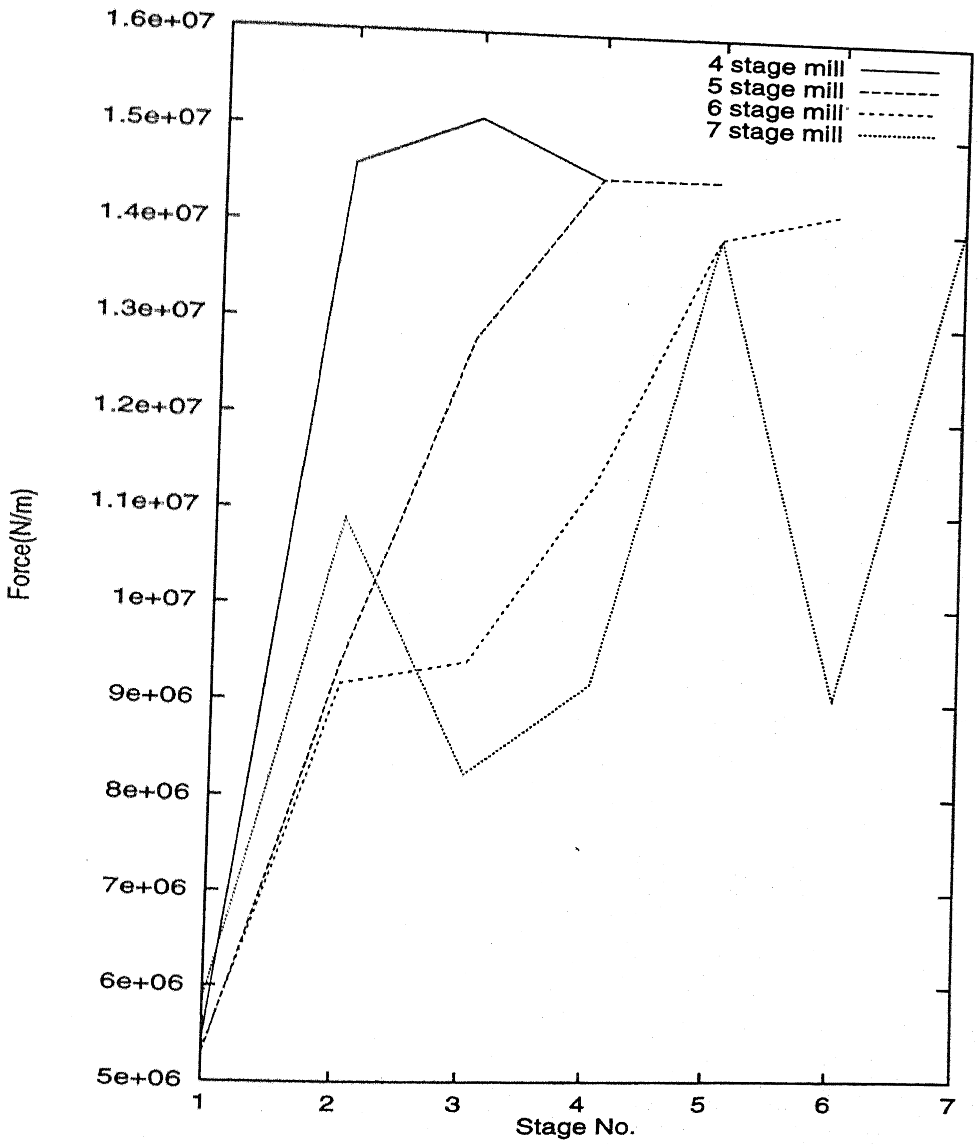


Figure 5.5: Variation of roll-separating force over various stages for maximization of production rate.

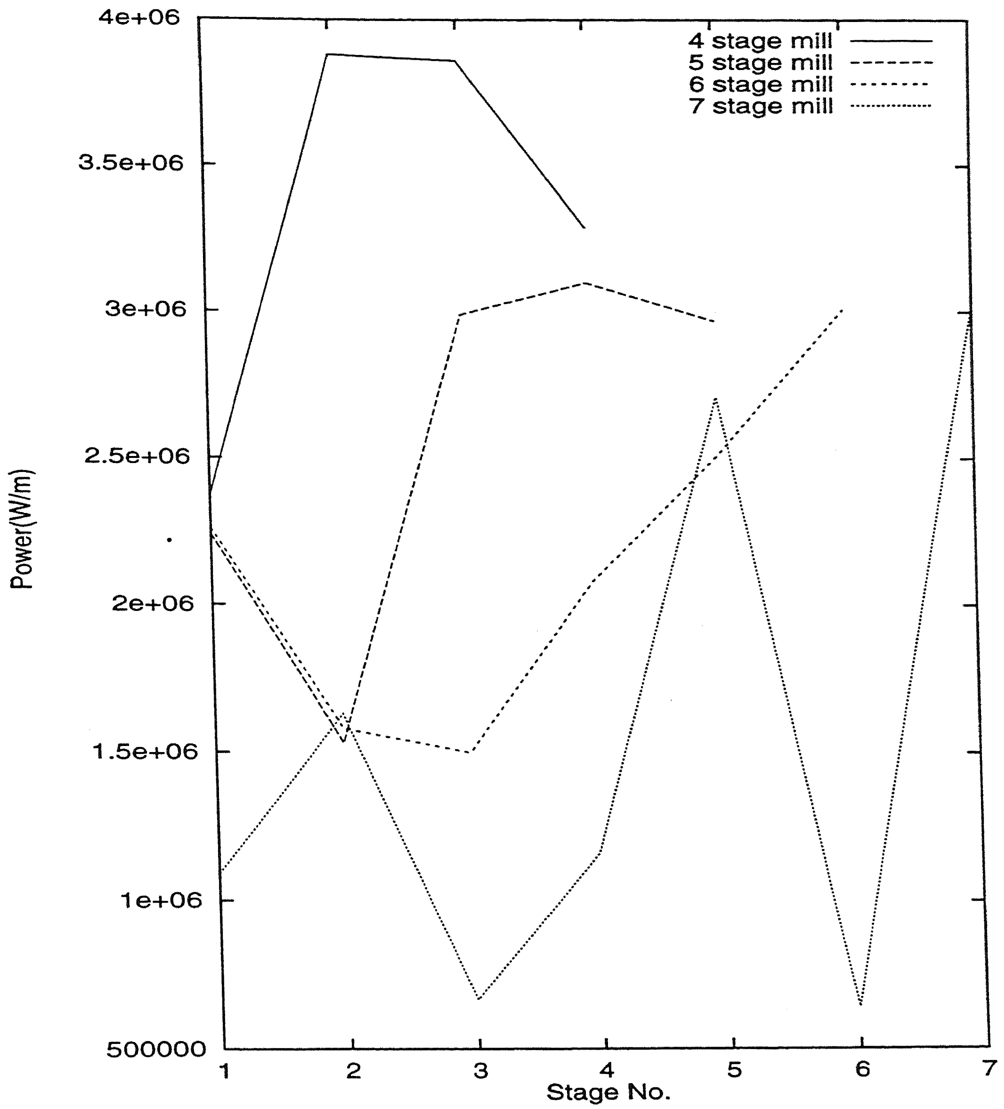


Figure 5.6: Variation of power over various stages for maximization of production rate.

Stage No.	Reduction (%)	Force (N/m)	Velocity (m/sec)	Power (W/m)	Inter-stand tension (N/m^2)
1	20.45	1.46×10^7	3.00	1.35×10^6	
					1.20×10^7
2	14.68	1.35×10^7	3.52	8.94×10^5	
					1.25×10^7
3	15.10	1.46×10^7	4.15	1.01×10^6	
					1.25×10^7
4	12.94	1.43×10^7	4.77	1.08×10^6	
Total Power=4.33×10^6W/m					

Table 5.9: Process parameters for 4 stage mill for optimization of power and production rate by giving equal weightage.

Stage No.	Reduction (%)	Force (N/m)	Velocity (m/sec)	Power (W/m)	Inter-stand tension (N/m^2)
1	20.30	1.45×10^7	3.00	1.32×10^6	
					1.06×10^7
2	9.60	1.09×10^7	3.33	5.44×10^5	
					1.22×10^7
3	13.14	1.33×10^7	3.83	8.37×10^5	
					1.33×10^7
4	10.72	1.28×10^7	4.29	6.88×10^5	
					1.32×10^7
5	10.21	1.31×10^7	4.78	8.76×10^5	
Total power=4.26×10^6W/m					

Table 5.10: Process parameters for 5 stage mill for optimization of power and production rate by giving equal weightage.

Stage No.	Reduction (%)	Force (N/m)	Velocity (m/sec)	Power (W/m)	Inter-stand tension (N/m^2)
1	18.05	1.33×10^7	3.00	1.16×10^6	
					1.10×10^7
2	9.92	1.08×10^7	3.34	5.59×10^5	
					1.18×10^7
3	5.21	8.87×10^6	3.53	3.04×10^5	
					1.33×10^7
4	8.31	1.10×10^7	3.85	5.00×10^5	
					1.29×10^7
5	10.83	1.27×10^7	4.31	7.18×10^5	
					1.32×10^7
6	12.37	1.40×10^7	4.92	1.08×10^6	
Total power=4.32×10^6W/m					

Table 5.11: Process parameters for 6 stage mill for optimization of power and production rate by giving equal weightage.

Stage No.	Reduction (%)	Force (N/m)	Velocity (m/sec)	Power (W/m)	Inter-stand tension (N/m^2)
1	15.14	1.16×10^7	3.00	9.67×10^5	
					1.11×10^7
2	8.36	9.66×10^6	3.28	4.57×10^5	
					1.19×10^7
3	8.26	1.03×10^7	3.58	4.89×10^5	
					1.29×10^7
4	5.44	9.21×10^6	3.79	3.20×10^5	
					1.34×10^7
5	11.95	1.30×10^7	4.30	8.19×10^5	
					1.45×10^7
6	3.96	9.33×10^6	4.48	2.58×10^5	
					1.38×10^7
7	12.11	1.39×10^7	5.10	1.10×10^6	
Total power=4.41×10^6W/m					

Table 5.12: Process parameters for 7 stage mill for optimization of power and production rate by giving equal weightage.

Optimum number of stages=5

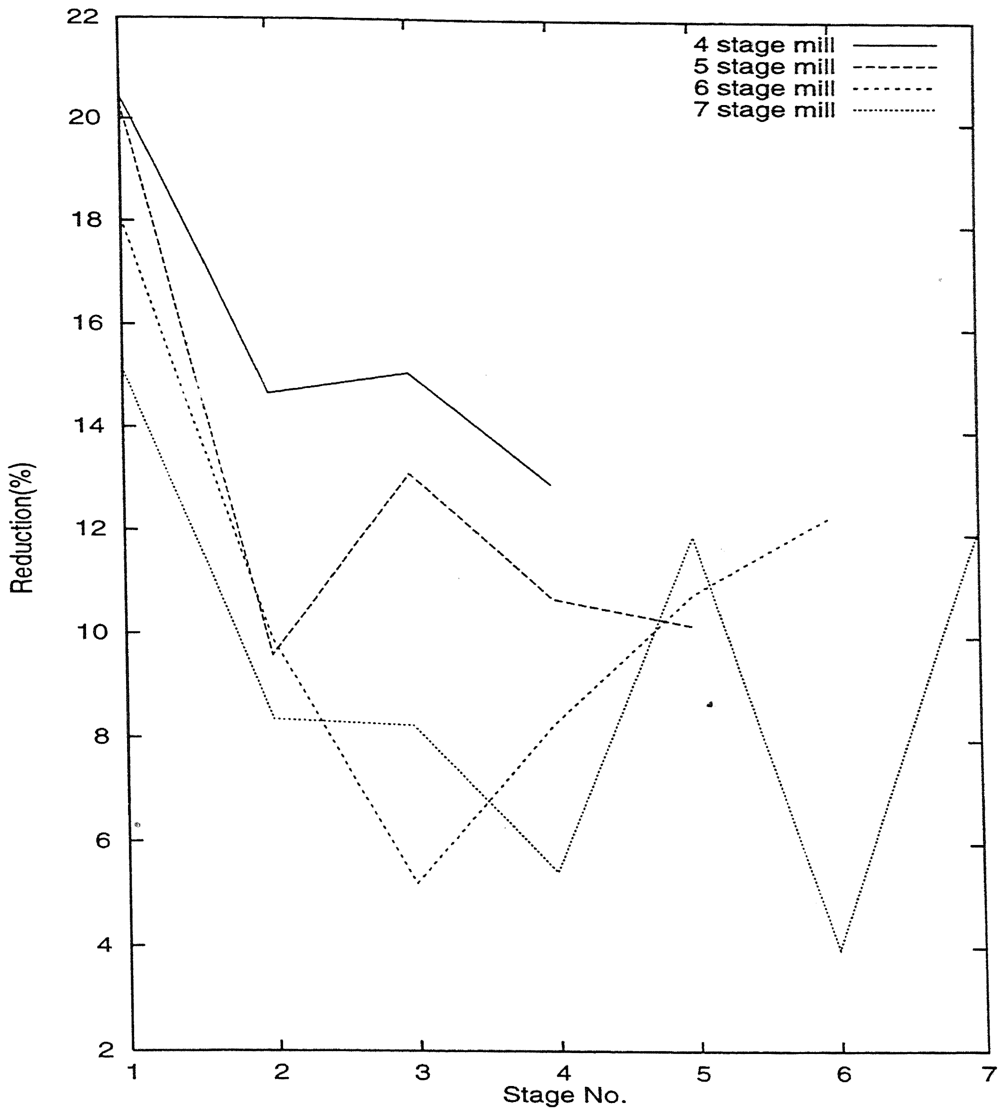


Figure 5.7: Distribution of reduction over various stages for optimization of power and production rate.

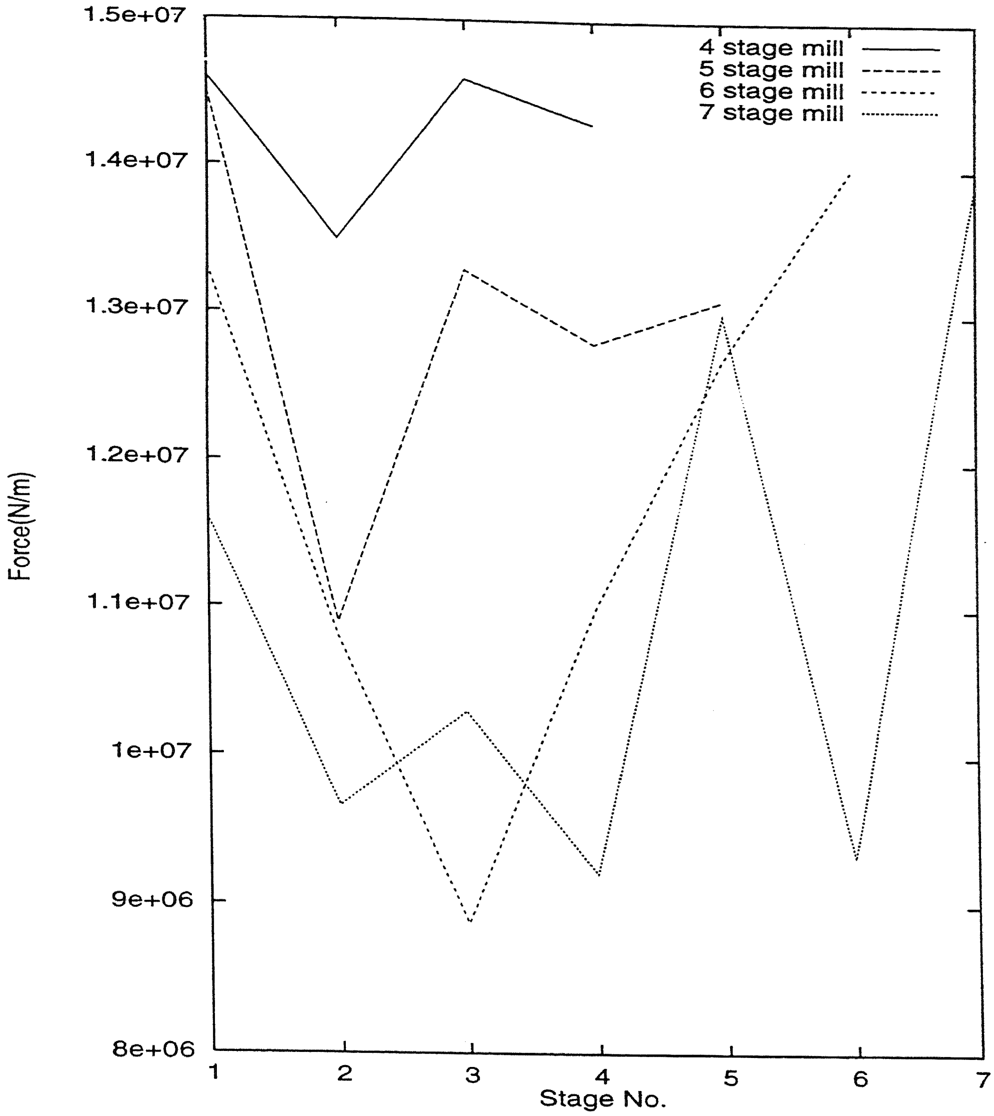


Figure 5.8: Variation of roll-separating force over various stages for optimization of power and production rate.

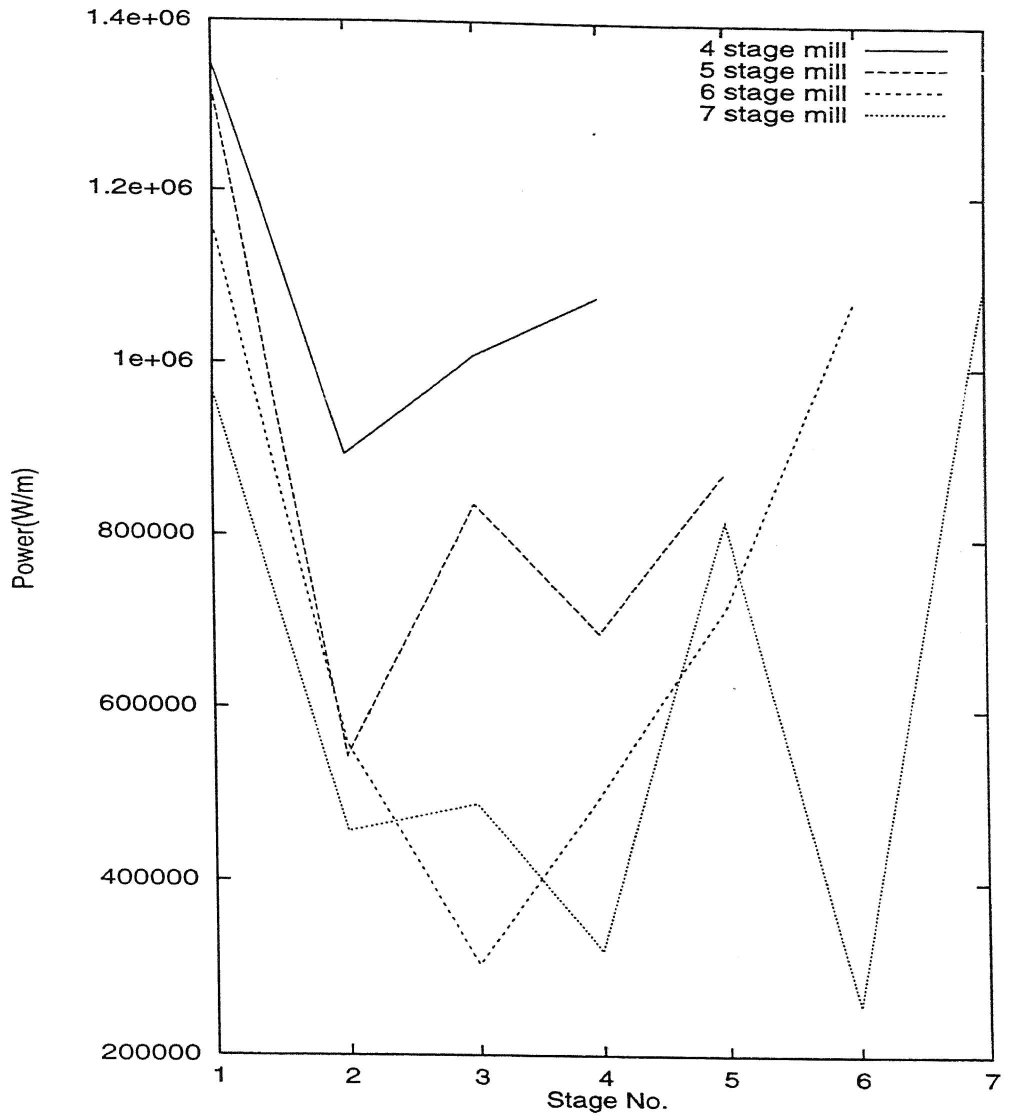


Figure 5.9: Variation of power over various stages for optimization of power and production rate.

Chapter 6

Conclusion and Scope for Future Work

6.1 Conclusion

The parameter optimization module for CAPP system of tandem cold rolling mill has been developed using a combination of generative and variant approaches for tandem cold rolling mill. A proper blend of knowledge based representation of thumb rules for selecting roll and lubricant parameters and an algorithmic approach for obtaining optimal rolling parameters appears to be successful strategy for process planning. The developed optimization model based on real coded genetic algorithm technique has the capability of evaluating the optimum process parameters for the practical rolling operation.

The module has been prepared for the objectives of minimization of overall power, maximization of production rate and bi-objective optimization of power and production rate by giving weightages as desired. Results indicate that for minimization of overall power and bi-objective optimization of power and production rate (with equal weightage), the overall power does not vary significantly on increasing the number of stages. Whereas for maximization of production rate the variation in overall power is significant. Therefore, the number of stages can not be selected solely on the consideration of overall power.

It has also been observed that in genetic algorithm the optimum value of the function depends on various GA parameters such as maximum number of generations , population size, cross-over and mutation probabilities. Therefore, one can always obtain a different optimum value by varying these parameters.

6.2 Suggestion for Future Work

1. In the present parameter optimization module the interstand tensions have been varied within the prescribed ranges and optimum values have been evaluated by optimization. If required, mathematical model for evaluating the interstand tensions can be developed.
2. Present work relates to cold rolling. By following the same procedure optimization module for hot rolling can also be prepared.
3. Present work needs to be verified with other non-linear optimization models because in case of genetic algorithm the optimum value of the function is changed by varying the GA parameters .
4. Some more objectives like minimization of total cost can be considered.

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